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Evaluation of ultrafine spiral concentrators for coal cleaning

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Evaluation of Ultrafine Spiral Concentrators for Coal Cleaning

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ABSTRACT

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Although froth flotation methods are the major processes being used in treating ultrafine coal in coal preparation plant, the processes might require large quantities of frother and collectors. The usage of reagents not only might increase the operating costs, but also cause environment concerns. 4+3 short turns two-staged spiral concentrator has been developed, applied in ultrafine coal cleaning circuit, and operated at a lower flowrate than that of spiral used in fine coal cleaning circuit. Ultrafine spiral concentrator is a specific gravity-based separator. It might be gradually accepted in ultrafine coal cleaning circuit as an alternative to froth flotation methods in ultrafine coal cleaning circuit of coal preparation.

To evaluate the ultrafine spiral in-plant separation performance, in-plant coal samples are collected from an ultrafine coal cleaning circuit in a coal preparation plant processing medium volatile bituminous coal in West Virginia. Detailed wet particle sizing and float-sink analysis using Lithium Metatungstate heavy liquid, are conducted at various particle size intervals. The particle size effects on the separation performance of ultrafine spiral to produce clean coal, and clean coal+middlings products were are evaluated. The characteristic parameters for the performance distribution curves, include the values of probable error, Ep, specific gravity separation, SG50, and the coefficient of variation, CV are derived by curve-fitting to in-plant separation performance data. Those parameters have the values of Ep~0.47-0.12, SG50~2.1-1.5, and CV~0.162-0.04 for clean coal, and Ep~0.44-0.12, SG50~2.50 -1.52, and CV~0.24-0.15 for coal+middlings. A narrow size interval would be desired for optimum separating efficiency because the better separation occurred to the different particle size intervals with different operation conditions. This study also finds that the ash contents of spiral clean coal, and clean coal+middlings products are affected by the misplaced particles of plus 150μm and minus 45μm introduced by the inefficiency of ultrafine spiral feed classifying cyclone. To maintain the high quality of products, desliming the product using clean coal classifying cyclone becomes necessary to remove high clay particles in minus 45μm size interval.

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Finally, this thesis is dedicated to the author's parents, and sister for their continuous caring and encouragement

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CHAPTER 1 INTRODUCTION

Coal preparation is the removal of undesirable materials from raw coal by employing various types of separation processes. Those processes are based on the differences between the physical or surface properties of coal particles and the impurities in raw coal. There are varieties of concentrating devices available to process different particle size fractions of raw coal (Peng, 2009).

For coal cleaning, the specific gravity-based concentration is not efficient as the particle size reduced below 150 μm due to higher specific gravity of separation (SG50, cut-point) and low sharpness of separation. Froth flotation technology based on coal and mineral surface property difference, are commonly used for ultrafine coal concentration. Froth flotation of fine coal is well known for its high separation efficiency. However, froth flotation has many inherited disadvantages.

For froth flotation technique, it might not efficiently treat middling particles. For A particle contained 10% coal on the surface has a good probability to float. Due to its relatively high specific gravitiy, the middlings may be rejected in a specific gravity-based concentrator. For this reason, the gravity-based concentrators are fundamentally superior to the froth flotation techniques (Adel et al., 1989; Honaker et al., 1995; Honaker et al., 1998) to treat finer raw coal. In froth flotation, flotation reagent consumption, and a high capital cost per unit of floor area for applying continuous stirred tank cells, can also be the major concerns. Flotation reagents usually constitute approximately 2-3% of total operating cost of the coal preparation plant (Laurila, 1998, Laurila, 2000). Unlike the specific gravity based concentrators, the froth flotation techniques involve complex physic-chemical interactions. Plant operators need more knowledge and patience in operating froth flotation systems. Hence, most operators are less inclining to operate this type of system (Jain, 2003).

Therefore, much of the effort has focused on the development of specific gravity-based concentrators for cleaning coal particle size less than 150 µm. Specific gravity-based concentrators have the potential to be more selective than alternative technologies such as froth flotation. Besides, the specific gravity-based separation principles are better understood by the typical plant operator. Based on recent publication (Honaker, et al., 2007; Benasa, 2007, and Mathew et al., 2008), spiral concentrators have the ability to achieve effective separations for particle size fraction of less than 150 µm down to 45 µm.

The objective of this study is to evaluate the effectiveness of in-plant ultrafine spiral concentrators for cleaning ultrafine coal at size interval of -150µm+44µm. The particle size effect on the separation efficiency of ultrafine spiral will be analyzed. The relationship of particle size and the characteristic parameters of performance distribution curves of ultrafine spiral will be derived.

CHAPTER 2 LITERATURE REVIEW

2.1 Separation processes for coal cleaning

Coal preparation involves processing to achieve the required quality for end users. It is estimated that 636 mt of coal were processed annually in U.S. The processes used in coal preparation are largely determined by washability of raw coal, variability of plant feed sizes, and the market specifications for the final products. Thus, raw coal is sized and cleaned in various coal cleaning circuits as shown in a typical coal cleaning flowsheet given in Figure 2.1.

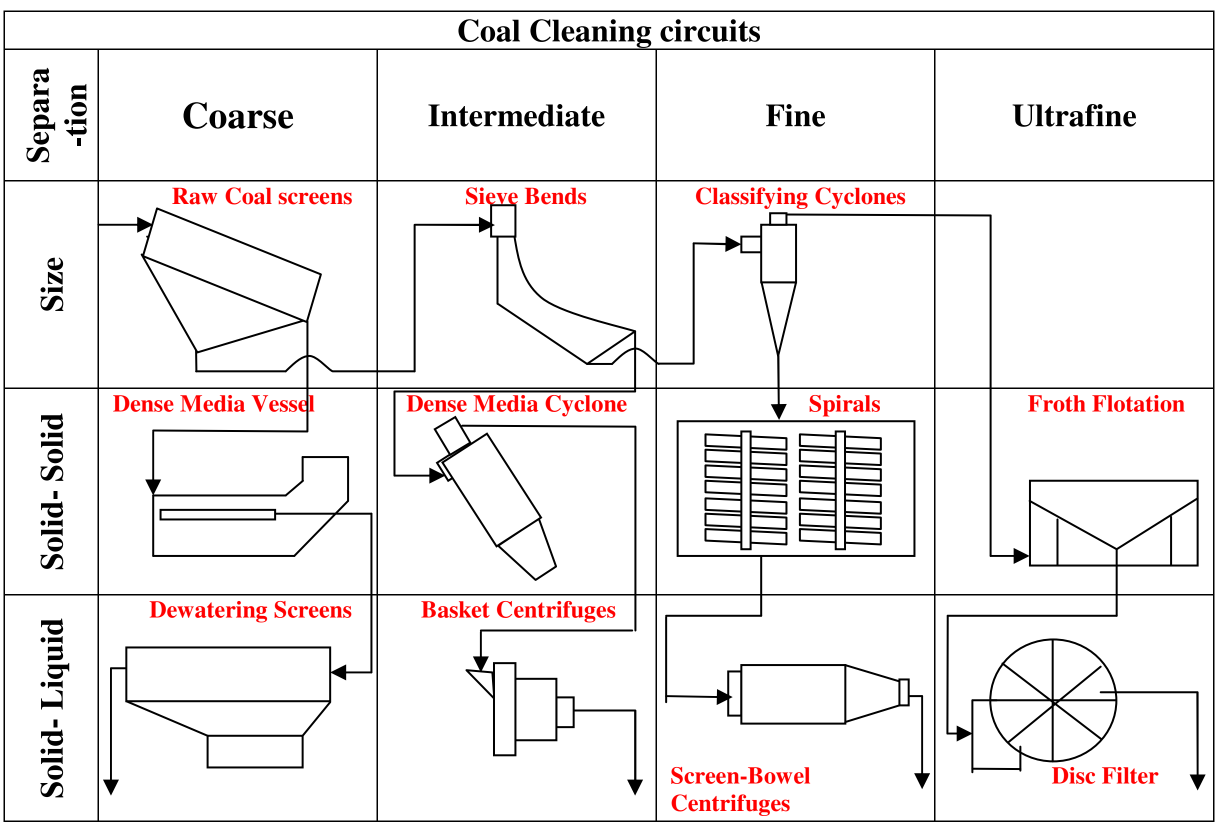

Figure 2.1 Typical coal cleaning flowsheet

2.2 Fine coal cleaning circuit and froth flotation circuit

Dense medium (DM) separation such as DM vessels or DM cyclones can efficiently clean coarse and intermediate raw coal to obtain products with high qualities. However, fine coal is difficult to concentrate efficiently with existing coal concentration devices. In the past, the common practice of discarding fines directly to impoundments is justified due to the cost of fines recovery, increased difficulty in dewatering as well as fine product handling. The current trend for processing coals has been shifted towards clean coal recovery maximization, which favors fine coal recovery due to increasing energy prices, decreasing energy reserves (including coal, oil and natural gas), and technology improvement. Several processes are available for fine coal cleaning to meet the requirements of growing emphasis on coal product quality.

For fine coal particle size less than 0.1 mm, fine spiral concentrator along with teeter-bed separators (hindering settling separator) are most appropriate choices in coal preparation plants (Kohmuench et. al., 2006). A teeter-bed separator consist of an open top, and the liquid fluidized column cell with elutriation water which is introduced through a series of distribution plates or spargars spaces across the base of the column cell. Feed is injected into the center, upper portion of the column cell. The settling particles encounter the upward flow of elutriation water, creating a fluidized teeter-bed of suspended particles. The small or light particles concentrate in the upper portion of the separator and are eventually carried over the weir at the top of the cell into a clean coal launder, while the large or heavy particles settle to the bottom of the cell and are discharged to refuse stream (Peng, Xia, and Gu, 2006).

Fine coal below 0.1 mm typically accounts for about 15% of feed (95mt annually) (Honaker et. al., 2007). Traditionally, Spiral separator is viewed as a fine coal cleaning concentrator Figure 2.2 shows the fine spiral coal cleaning circuit and froth flotation ultrafine coal cleaning circuit. However, spiral separator in the treatment of fine coal is now gradually being introduced as an alternative to froth flotation in ultrafine coal cleaning circuit, by utilizing low solid concentration and slower slurry feed rate. This can be due to no reagents being used and misplace of pyritic sulfur to products can be minimized.

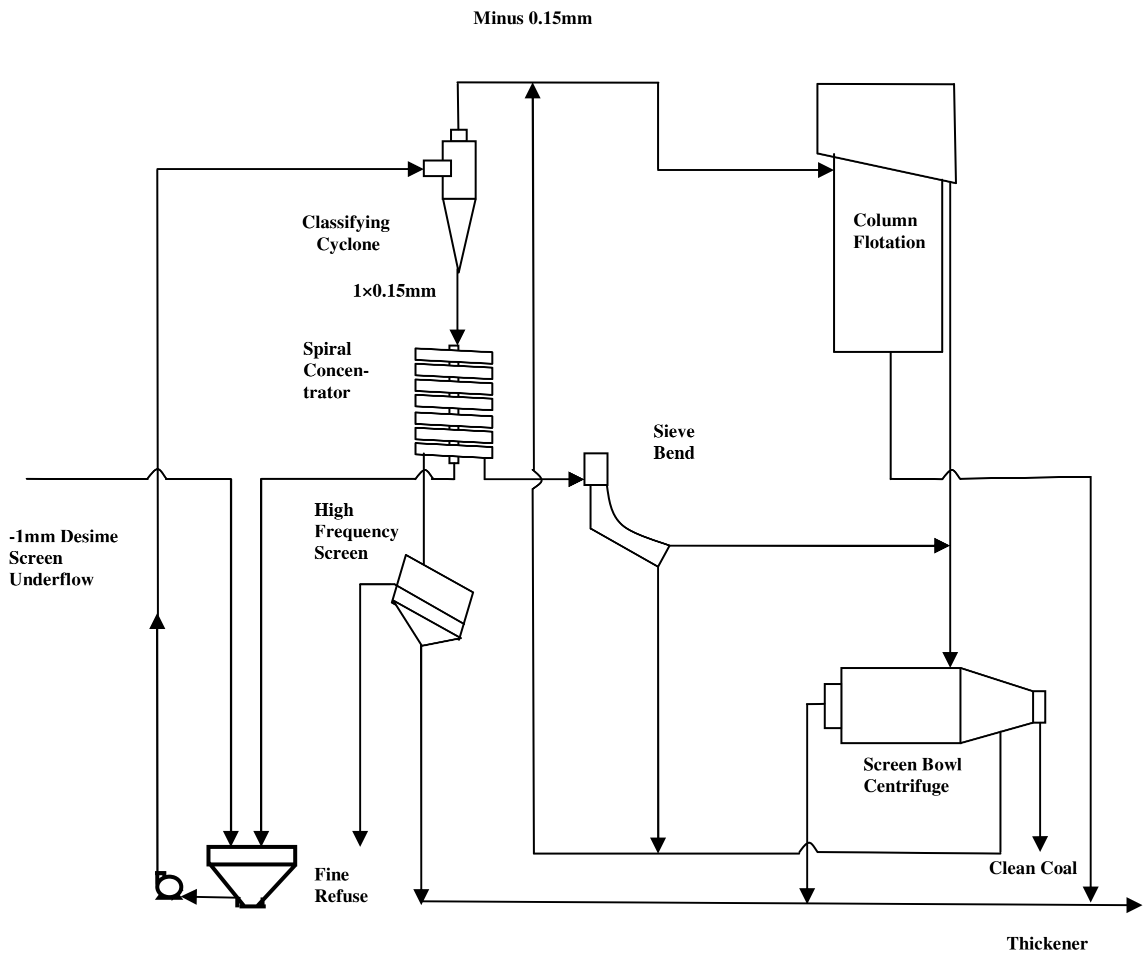

Figure 2.2 Fine coal circuit and flotation circuit

2.3 Spiral performance improvements

Spirals are specific gravity-based concentrator for cleaning fine coal in the size range of 2-3 mm to 0.1 mm (Burt 1984; Palowitch et al., 1991, Kapur and Meloy, 1999). From yearly production experiences and development efforts, spirals become one of the most effective methods for cleaning the fine coal within a size range from 1 mm to 0.1 mm (Luttrell, 2004; Bethell and Arnold, 2003). Fine coal spirals with triple starts are exhibited in Figure 2.3 (a), while two stage spirals are exhibited in Figure 2.3 (b). Spiral concentrator has the following advantages: low cost, high separation efficiency, and ease of operation (MacHunter et. al., 2003; Weldon, 1997). However, the shortcomings of spiral concentrator include relatively high specific gravity of separation, SG50 (cut-point), relatively low unit throughput, the need for multi-stage processing, and limited acceptable feed size range (MacHunter et. al., 2003; Kohmuench, 1998). In particular, SG50 value of spiral concentrators is greater than 1.70, which is much higher than those of the dense medium vessels for coarse coal cleaning (< 1.60 SG50). This results in either a loss of much of clean coal in tailings or a decreasing in clean coal quality (DTI, 2001).

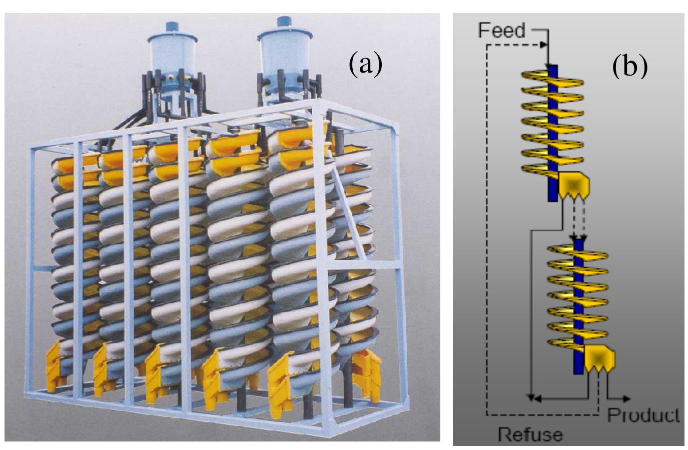

Figure 2.3 (a) Fine coal three start spirals; (b) Two stage spirals

As described in previous section, one of disadvantage of using spirals is the operating condition, SG50 value at 1.70 or higher. Spirals are thus often operated in two stage units as shown in Figure 2.3 (b), to produce the products to meet the requirements. Recent development has been aimed at lowering SG50 value and improving selectivity. One notable development has been the introduction of compound spiral concentrator systems. In this system, two "4+ 3 short-turn" spirals are mounted in series on a common spiral column, to achieve a two-stage separation in a single unit. One of this type of unit operations is known as SX7 coal spiral. SX7 coal spiral is exhibited in Figure 2.4. This two short turn compound spirals are increasing in applications for the concentration of fine coal in coal preparation plant. Efforts were also made to standardize the required number of turns needed on a spiral separator for different ores. A 5 to 7 turn spirals were recommended to achieve optimum recovery, and to achieve the required separation performance (Holland-Bratt, 1995).

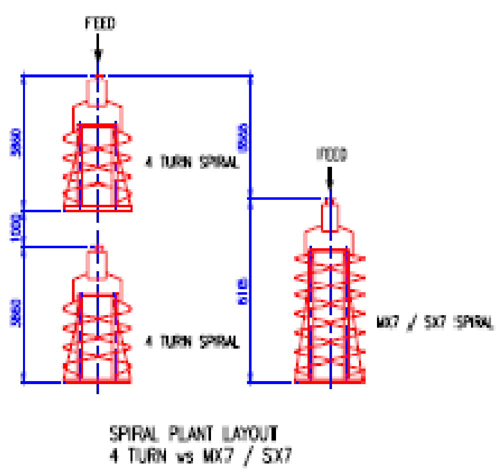

Figure 2.4 4+3 short turn two staged spiral-SX7

As mentioned before, high SG50 value is a shortcoming of spiral separation. To address this disadvantage, spirals are also employed in multi-stage circuits where the clean coal and/or middling streams from primary spirals are re-suspended and reprocessed in secondary spirals. The improvement in separation performances compared of a single spiral for those configurations are summarized in Table 2.1(Luttel, 2004).

Table 2.1 The separation performance of different spiral circuit configurations

Parameters	**Single-stage (a)** **(No recycle)**	**Two stage (b)** **(No recycle)**	**Two stage (c)** **(recycle)**
Circuit yield (%)	56.7	40.6	46.3
Circuit ash (%)	18.8	9.05	9.23
Separation sharpness (Ep)	0.18	0.20	0.15
Organic Efficiency (%)	90.4	83.4	94.3
SG Cutpoint	1.82	1.61	1.66

SX7 spirals were developed four spiral turns followed by the removal of a primary refuse and re-mixing of the middlings and clean coal. No water is added to the remixer (or repulper). The middlings and clean coal then are treated on three additional spiral turns. A splitter at the bottom of the spiral allows removal of a secondary refuse that can be combined with the primary refuse. A middlings can also be collected and fed back to the feed for re-processing or can be combined with the clean coal product. The two-stage circuit for fine coal cleaning decreases the Ep value from around 0.15 to 0.135, which enhanced organic efficiency by five percentage points. The Benefits of two-Stage Coal Spirals (SX7) are summarized as follows.

- Advantages of double stage circuit, but in one spiral assembly

- Reduce cost while improving performance
- Reduction in capital equipment cost, overall plant height and floor area
- Four spiral turns followed by removal of a primary refuse
- Remixing of middlings and clean coal followed by three spiral turns
- Stream is split into secondary refuse, middlings and clean coal
- Middlings to be recycled to feed

2.5 Ultrafine coal cleaning circuit

Froth flotation in the United States is applied generally to minus 250 µm (USA Series No. 60) ultrafine coal. In some cases, this size fraction is deslimed at 45 or 38 µm (USA Series No.325 or 400) prior to cleaning in froth flotation cells. For some coals in the United States, froth flotation is not an option. Some coals are relatively low in rank and require an uneconomical amount of reagents to be added. Others produce a froth that is so strong that difficult to dewater due to persistent of foam. Pyrite sulfur is an issue, and will be recovered with the froth product. To address some of these concerns and provide a lower operating cost option, Sedgman developed an ultrafine spiral circuit (Arnold, 2003, 2006) incorporating with small diameter classifying cyclones for cleaning the -150+45μm size interval of ultra fine coal as illustrated in Figure 2.5. This figure shows a coal preparation plant near Central City, Pennsylvania (PA). It is a typical fine and ultrafine coal cleaning circuits in U.S., which includes classifying cyclones ahead of fine and ultrafine spirals. The similar fine and ultrafine spiral coal cleaning circuits in coal preparation plants have been installed in Illinois, Ohio, Pennsylvania, and West Virginia.

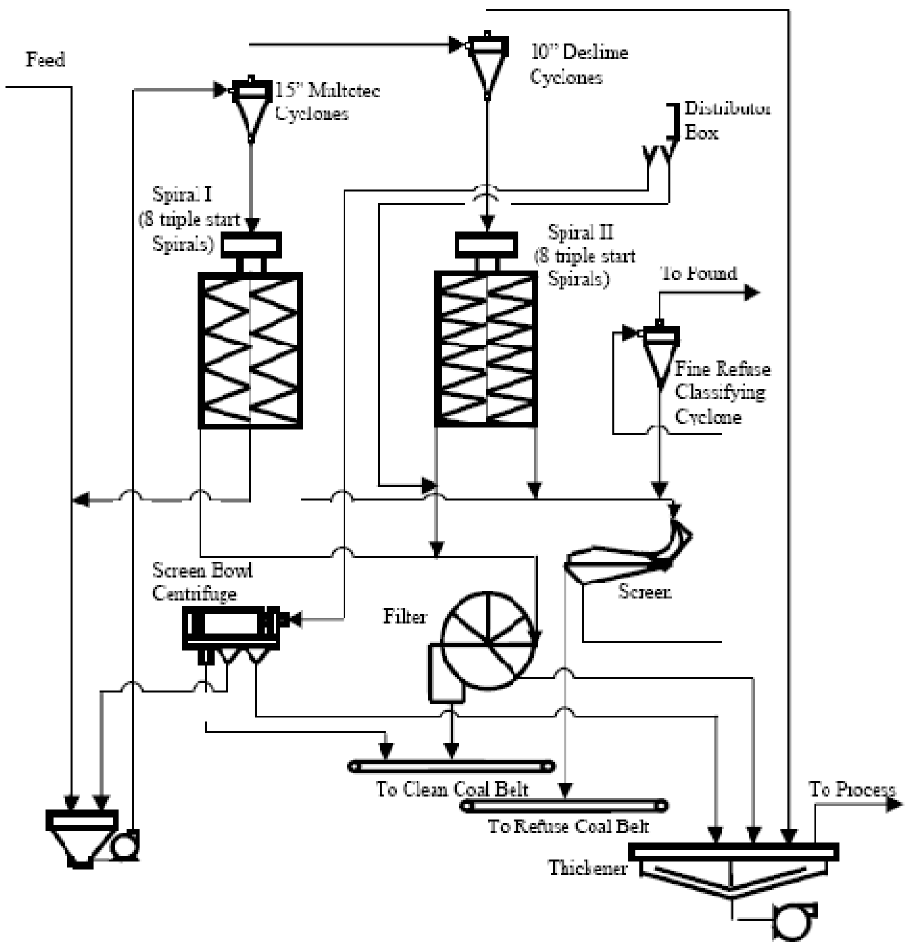

Figure 2.5 Spiral separation flowsheet at a coal preparation plant, PA (Che, 2009)

Bench scale testing of the ultrafine spiral was conducted by (Jian 2003) and Honaker et al (2007). The coal sample is from the Coalburg seam in Southern West Virginia from underflow of banana desliming screen in coal preparation plant. All the tests were conducted using a single-start LD4 spiral (MDL, Australia). Their test results showed that the -210+45 μm particles require greater residence time and lower feed solid concentrations for effective separation implies the need of lower feed rate. Performance SG50 as low as 1.8 can be achieved using a single stage spiral treatment with probable error value of Ep = 0.2-0.25. The product ash of 10% were achieved at maximum recovery by adjusting the feed rate from 30 lpm to 46 lpm, feed solid concentration of 12%-15% wt, and splitter position at 30 cm. This equated to 0.25-0.4 tph. They obtained data from washability analysis but comparable to those from the release analysis. This implies that potential of ultrafine spirals to treat the ultrafine coal rather than flotation. A pilot scale circuit was subsequently installed at Alliance coal, coal preparation plant in White County, Illinois in 2002. The result also led to the first installation of commercial scale of ultrafine spiral coal cleaning circuit to treat Illinois No. 6 seam coal at the same plant in 2003. The pilot and in-plant study show that spiral feed has 12 % solid by weight. The volumetric feed flowrate was 70 lpm (0.6 tph). The ash and sulfur contents in clean coal product were 11.8%, and 2.64% while ultrafine spiral feed had 19.33% and 3.37% sulfur, respectively. To obtain the acceptable product, the minus 45 µm particle size interval (45.66% ash in clean coal) needed to be removed by additional product classifying cyclone.

Pilot scale ultrafine spiral testing was conducted by Benusa (2007), and Benusa and Klima (2008) using a 4+3 two-staged SX7 spiral concentrator to treat nominal -150 µm bituminous coal in Central Pennsylvania (PA). Those authors investigated the effects of slurry flow rate and solids concentrations on ultrafine spiral separation performance. Ten spiral tests were conducted using the deslimed material at flow rates of 75 lpm and 45.5 lpm for solid concentrations of 31%, 25%, 20%, 15% and 10%. Six spiral tests were conducted using undeslimed material at flow rate of 103.5, 75, and 45.5 lpm for including solid concentrations of 28% and 18%. The spiral feed with ash value of 11.4% has been reduced to a clean coal ash value of 10.3% with a yield of 80% at a flow rate of 75 lpm and a solid concentration of 31%. Similar results were obtained at a flow rate of 45.5 lpm and a solid concentration of 10%. A low rate of 45.5 lpm with a solid concentration of 3d1% could achieve a clean coal ash value of 9.8% with a yield of 66.3%. The spiral concentrated sulfur particles in the refuse stream, as seen by the refuse sulfur content of 2.5% compared to 1.4% in the feed, while producing clean coal with a sulfur content of 1.3%. The addition of minus 25µm (-500 mesh) material, has little effect on overall spiral performance. However, the removal of the minus 25µm (-500 mesh) material will be necessary to reduce the ash content of the clean coal product.

The fine and ultrafine spiral circuits in coal preparation plants generally consist of three to four stages of classification of spiral feeds, and products (Arnold, 2004, 2006) to achieve the products' qualities.

1) Fine raw coal classifying cyclones – Pre-ultrafine spiral circuit
2) Desliming cyclones – Pre-ultrafine spiral circuit
3) Clean coal product classifying cyclones – Post fine spiral circuit. Overflow is used for spray water of raw coal screen
4) Clean coal product desliiming classifying cyclones – Post ultrafine spiral circuit. Remove overflow to thickener

Generally, the ultrafine spirals operate at a slightly higher SG50 values than spirals processing the coarser plus 0.15 mm size intervals due to the high degree of ash and sulfur liberation found in the ultrafine fine size interval, the quality of the clean coal product is typically equivalent or better than that achieved with the coarser size interval from fine spirals. Due to the success of the process circuitry and reductions in operating costs, the ultrafine spirals may be considered as an alternative method for froth flotation of fine coal in ultrafine coal cleaning circuit (Arnold and Petrunak, 2006).

CHAPTER 3 EXPERIMENTAL

3.1 Materials

Coal samples were collected from an operating coal preparation plant in Southern West Virginia (WV). The plant is processing a medium volatile bituminous coal. The coal preparation plant flowsheet consists of a banana raw coal screen, heavy-media cyclones, classifying cyclones, fine and ultrafine spirals, and dewatering devices. Figure 3.1 presents the fine and ultrafine coal cleaning circuits associated with spiral separation. Two sets of spirals are installed in the plant. One set of triple-start spirals referred to as "fine spiral concentrator" treat the underflow of the primary cyclones having particle size of -1.0 mm+150 μm. Three products are generated from each fine spiral: clean coal, middlings, and refuse. Another set of triple-start spirals referred to as "ultra fine spiral", cleaning the underflow of the secondary cyclones with the particle size interval of -150+45μm. The middlings of both spirals are mixed with clean coal as final product. Consequently, only clean coal+middlings are collected from fine and ultrafine coal cleaning circuits in-plant.

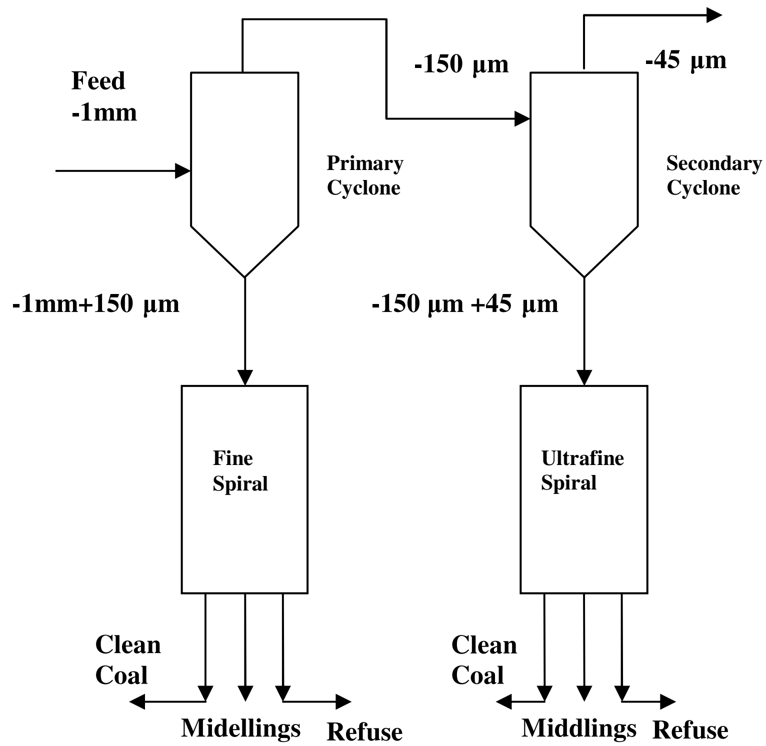

Figure 3.1 Fine and ultrafine coal cleaning circuits

3.2 Sampling collection and preparation

Wet coal samples were collected in 5 gallons sample pals, which were collected every 30 minutes interval from a coal preparation plant in South, West Virginia (WV). Ccoal samples include the underflow of primary cyclone and secondary cyclone, clean coal, middlings and refuse for fine and ultrafine spirals, respectively. After settling, the coal samples were decanted to remove supernatants. Then, the coal samples were spread in the large and shallow pans, and placed and dried in a ventilation oven at 50°C. Once coal samples are dried, each coal sample was thoroughly mixed for subsequent tests including, particle size analysis and float-sink tests.

3.3 Particle size distribution analysis

Size distribution analyses are conducted for the coal samples of clean coal, middlings, refuse and feed of fine and ultrafine spirals, respectively. The following sieves are used for fine coal spiral: +2mm (US series, -No.10), -2mm+1680µm (US series, -No.10+No.12), -1680µm+1400µm (US series, -No.12+No.14), -1400µm+1000µm (US series, -No.14+No.18), -1000µm+600µm (US series, -No.18+No.12+No.30), -600µm+250µm (US series, -No.30+No.60), -250µm+150µm (US series, -No.60+No.100) and -150µm (US series, -No. 100). For ultrafine spirals, the particle size intervals are +600µm (US series, No.30), -600µm+250µm (US series, -No.30+No.60), -250µm+210µm (US series, No.60+No.70), -210µm+150µm (US series, -No.70+No.100), -150µm+75µm (US series, No.100+No.325), -75µm+45µm (US series, -No.200+No.325), and -45µm (US series, No. 325). Wet sieving method was applied for coal particle paticle size distribution analysis. This method uses water as a medium for facilitating the segregation of the coal sample into sieveable particle sizes. The detail steps are given in Appendix A-1.

3.4 Float-sink tests

Float-sink tests are carried out for clean coal, middlings, and refuse of fine spiral and ultrafine spiral. Float-sink tests are performed for each size interval. Lithium Metatungstate (LMT) liquids at the specific gravities of 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0 and 2.3 are prepared in 4000 ml beakers for fine coal, and 1000 ml separatory funnels are prepared in 1000 ml separatory funnels for coal float-sink tests at the specified particle size intervals. Details of test procedures are given in Appendix A-2. For determination of ash content in each coal sample is follow the procedure of ASTM. Details of operation procedure are given in Appendix A-3.

3.5 Size distribution analysis, washability data analysis, and performance distribution curve analysis

Particle size distribution of feed for ultrafine spiral concentrator is reconstituted the float-sink test data by using following equations.

$$F \cdot f\, w_{ji} = C \cdot cw_{ji} + M \cdot mw_{ji} + R \cdot rw_{ji} \tag{3.1}$$

$$fa_{ji} = \frac{C \cdot cw_{ji} \cdot ca_{ji} + M \cdot mw_{ji} \cdot ma_{ji} + R \cdot rw_{ji} \cdot ra_{ji}}{F \cdot fwji} \tag{3.2}$$

$$F = C + M + R \tag{3.3}$$

where

f_j, ca_j, ma_j, and ra_j = ash content of particles at i-specific gravity interval and j-th particle size interval, for feed, clean coal, middlings, and refuse, respectively, %

fw_j, cw_j, mw_j, and rw_j = weight of material at i-th specific gravity interval and j-th particle size interval, w_j for feed, clean coal, middlings, and refuse, respectively, %

F, C, M, and R = yields of feed, clean coal, middlings, and refuse, respectively, %

The performance distribution curves can be used to describe the separation efficiency of coal cleaning unit operations. Two characteristic parameters are directly derived from a performance distribution curve. The mathematical equation known as logistic function is used to fit the experimental data points of the separation performance based on the principle of least square technique.

$$K_{ji}(xj, SGi), \% = 100 \cdot \frac{1}{1+EXP\left[\left(\frac{1.098}{Epj}\right)(SGji - SG50j)\right]} \tag{3.4}$$

$$K_{ji}(xj, SGi), \% = 100 \cdot \frac{1}{1+EXP\left[\left(\frac{1.098}{Epj}\right)(SGji - SG50j)\right]}(a - b) \tag{3.5}$$

where

K_{ji} = Distribution factor reporting to clean coal, or clean coal+middlings at the i-th specific gravity interval and the j-th particle size interval, %

SG_{ji} = Specific gravity of the particles at i-th specific gravity interval and j-th particle size interval

$SG50_j$ = Specific gravity of separation (cut point), corresponding to 50% distribution factor at the j-th particle size interval

a= Low specific gravity by-pass. If a equals 0, there is no low specific gravity by-pass.

b= High specific gravity by-pass. If b equals 0, there is no high specific gravity by-pass.

The characteristic parameters of performance distribution curves including the values of probable error, Ep, specific gravity separation, SG50, as well as the coefficient of variation, CV are derived from curve fitting of performance distribution curves described in previous section. The Ep value represents a slope of performance distribution curve between 25 and 75 percentage ordinates. The mathematical equation for the slope can be expressed by the equation shown below. CV_j is also known as generalized inperfection. In many cases, CV_j can be a constant value.

$$\mathrm{Ep_j} = \frac{\mathrm{SG25_j} - \mathrm{SG75_j}}{2} \tag{3.6}$$

The coefficient of variation, CV_j is defined by the mathematical equation of

$$\mathrm{CV_j} = \frac{\mathrm{Ep_j}}{\mathrm{SG50}} \tag{3.7}$$

The particle sizes used in the correlation with performance characteristic parameters are geometric mean particle size, which is defined as

$$x_{j,j+1} = \sqrt{x_j \cdot x_{j+1}} \tag{3.8}$$

where

x_j and x_{2j+1} = particles sizes passing j-th and(j+1)-th sieves, respectively

$x_{j,j+1}$ = geometric mean particle size of x_j and x_{j+1}

Figure 3.2 shows a performance distribution curve for a separation process with by-passes. All the experiment data and data analysis results are given in Appendix B Particle size distribution data and analysis, Appendix C Washability data analysis, and Appendix D Weight versus Particle Size and Ash versus Particle Size data.

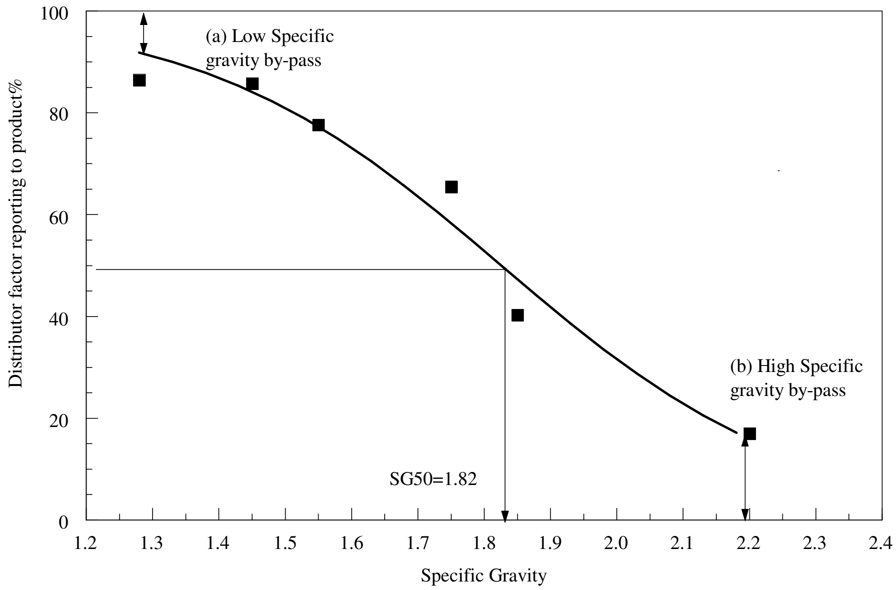

Figure 3.2 Performance distribution curve for a separation process with by-pass

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Reconstituted ultrafine spiral feed size distribution

The cumulative % passing particle size distribution is generated by cumulating the weight of material from the smallest size interval to the coarse size interval. The data of feed particle size distribution is given in Table 4.1. The reconstituted feed cumulative % passing particle size distribution curve for ultrafine spiral is plotted in Figure 4.1 The feed particle size distribution for ultrafine spiral according to the designed for ultrafine coal cleaning circuit, should be -150+45μm particle size range. Table 4.1 and Figure 4.1 show the misplaced particles of plus 150 μm is about 15%, and the misplaced particles of minus 45μm is about 35% by wt. Those high misplaced particles in the feed might contribute to high ash and sulfur contents in ultrafine spiral products.

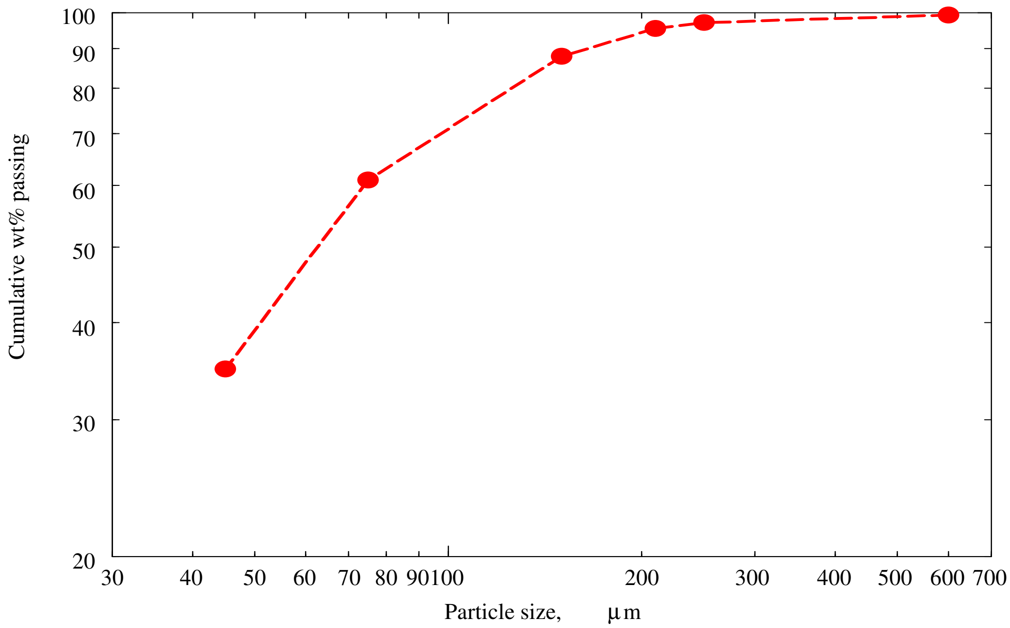

Figure 4.1 Reconstituted feed size distribution for ultrafine spiral concentrator

4.2 Float and sink tests of feed for ultrafine coal spiral

To construct the washability curves for the feed of ultrafine spiral feed, float and sink test data is calculated according to Eqs (3.1) (3-2) and (3.3) for reconstituted feed. There are seven paraticle size intervals for wet sieving. The particle size intervals are

Table 4.1 Reconstituted particle size distribution of feed for ultrafine spiral

Size (µm)	Direct							Cumulative			
	Feed	Clean coal Wt (%)	Middlings Wt (%)	Refuse Wt (%)	Clean coal Wt (%) of Feed	Middlings Wt (%) of Feed	Refuse Wt (%) of Feed	Feed	Clean coal Wt (%) of Feed	Middlings Wt (%) of Feed	Refuse Wt (%) of Feed
+600	0.66	0.27	0.32	1.51	0.14	0.05	0.47	100.00	53.00	16.00	31.00
-600+250	2.19	1.85	1.99	2.89	0.98	0.32	0.90	99.34	52.86	15.95	30.53
-250+210	1.66	1.85	1.61	1.36	0.98	0.26	0.42	97.15	51.88	15.63	29.64
-210+150	7.57	8.68	9.28	4.78	4.60	1.49	1.48	95.48	50.90	15.37	29.21
-150+75	26.92	32.99	19.25	20.51	17.48	3.08	6.36	87.91	46.29	13.89	27.73
-75+45	26.12	25.01	17.23	32.61	13.26	2.76	10.11	60.99	28.81	10.81	21.37
-45	34.87	29.35	50.33	36.33	15.55	8.05	11.26	34.87	15.55	8.05	11.26
Total	100.00	100.00	100.00	100.00	53.00	16.00	31.00				

+600μm (US series +No.30), -600+250μm (US series -No.30+No.60), -250+210μm (US series -No.60+No.70), -210+150μm (US series -No.70+No.100), -150μm+75μm (US series -No.100 +No.200), -75μm+45μm(US series -No.200+No.325), and -45μm (US series -No. 325). Three coarser size intervals are combined into plus 210 μm size interval due to small amount of particles for plus +600 μm, -600+250μm and -250+210 μm particle size intervals.

Table 4.2 shows the washablity data of reconstituted feed for ultrafine spiral concentrator. The results of washability data analysis of feed for ultrafine spiral are given in Figure 4.2. From ±0.1 near gravity materials curve, the separation of ultrafine raw coal will be easy at 1.80 or higher specific gravity, where ±0.1 near gravity materials are less than 10% during the preparation. The washability curves also show that the ash content of ultrafine coal feed is 20.3%.

Table 4.2 Washablity data of feed for ultrafine spiral

Specific Gravity Interval	Direct		Cumulative Float		Cumulative Sink		±0.1 near gravity material
	Wt %	Ash %	Wt %	Ash %	Wt %	Ash %	
< 1.30	36.15	4.91	36.15	4.91	100.00	20.30	
1.30 - 1.40	21.00	7.91	57.15	6.01	63.85	29.02	0.32
1.40 - 1.50	8.31	15.85	65.46	7.26	42.85	39.36	0.18
1.50 - 1.60	8.47	23.62	73.94	9.14	34.54	45.02	0.18
1.60 - 1.70	8.46	32.18	82.40	11.50	26.06	51.98	0.15
1.70 - 1.80	5.16	42.24	87.55	13.31	17.60	61.50	0.08
1.80 - 1.90	2.07	50.63	89.62	14.17	12.45	69.47	0.06
1.90 - 2.00	3.28	57.37	92.90	15.70	10.38	73.23	
> 2.00	7.10	80.56	100.00	20.30	7.10	80.56	

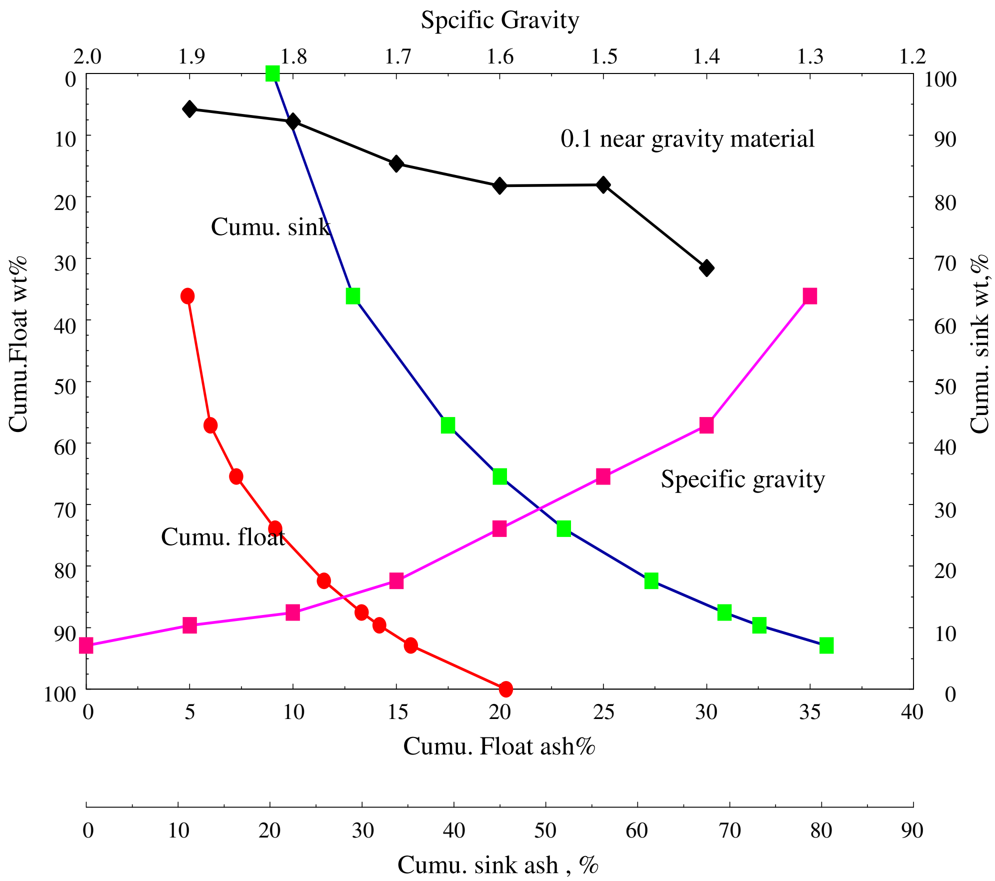

Figure 4.2 Washability curves of feed for ultrafine spiral

4.3 Correlation of weight and ash percentages of different size intervals for ultrafine coal spiral

Table 4.3 and 4.4 show particle size distribution (wt%) and ash% distribution of ultrafine spiral products: clean coal, middlings, and refuse. Figure 4.3 shows relationship of direct weight and ash percentages of ultrafine spiral products at different particle size intervals. For the feed of ultrafine spiral, plus 210 μm misplaced particles has as high as 7.0% direct ash content with 2% direct weight for middleings. On the other hand, minus 45μm misplaced particle has about 28.7% direct ash content with about 8% direct weight for middlings. Those misplaced particles in feed are due to inefficient separation of feed classifying cyclone. For those reasons, clean coal and clean coal+middlings products might require to deslime minus 45 μm misplaced particles to maintain the high quality of ultrafine spial products.

Table 4.3 Direct particle size distribution of the products for ultrafine spiral

Size Range	Direct Weight, %			
	Clean coal	Middlings	Refuse	Feed
+210mm	2.10	0.61	1.78	4.50
-210μm-150μ	4.60	1.61	1.48	7.68
-150μm+75μm	17.48	2.53	6.36	26.37
-75μm+45μm	13.26	2.55	10.11	25.92
-45μm	15.56	8.70	11.27	35.53
Total	53.00	16.00	31.00	100.00

Table 4.4 Direct particle ash content distribution of the products for ultrafine spiral

Size Range	Ash, %			
	Clean coal	Middlings	Refuse	Feed
+210mm	3.37	7.58	41.01	18.86
-210μm-150μ	4.10	6.83	13.19	6.42
-150μm+75μm	5.02	6.48	13.60	7.23
-75μm+45μm	8.37	15.73	30.32	17.66
-45μm	34.12	28.67	40.85	34.92

4.4 Grade-yield curve for ultrafine spiral products

Details of washability data for feed and products of ultrafine spiral are given in Table 4.5. For ultrafine spiral, clean coal, and clean coal+middlings have 53% yield with 14.3% ash, and 69% yield with 15.6% ash content, respectively. It can be seen that only 30.8% ash is rejected in ultrafine spiral. Figure 4.4 shows the grade-yield curve for the feed of ultrafine spiral. The data points are shown for two different products, one is clean coal as final product, and another is clean coal+middlings as final product. The solid line represents the cumulative float curve from the washability data of feed. This curve is the theoretical achievable grade-yield separation curve. Both ultrafine spiral products are far from the cumulative float curve. There are plenty of room to improve the separation performance of ultrafine spiral operation to approach to the cumulative float curve by optimizing the ultrafine spiral operations.

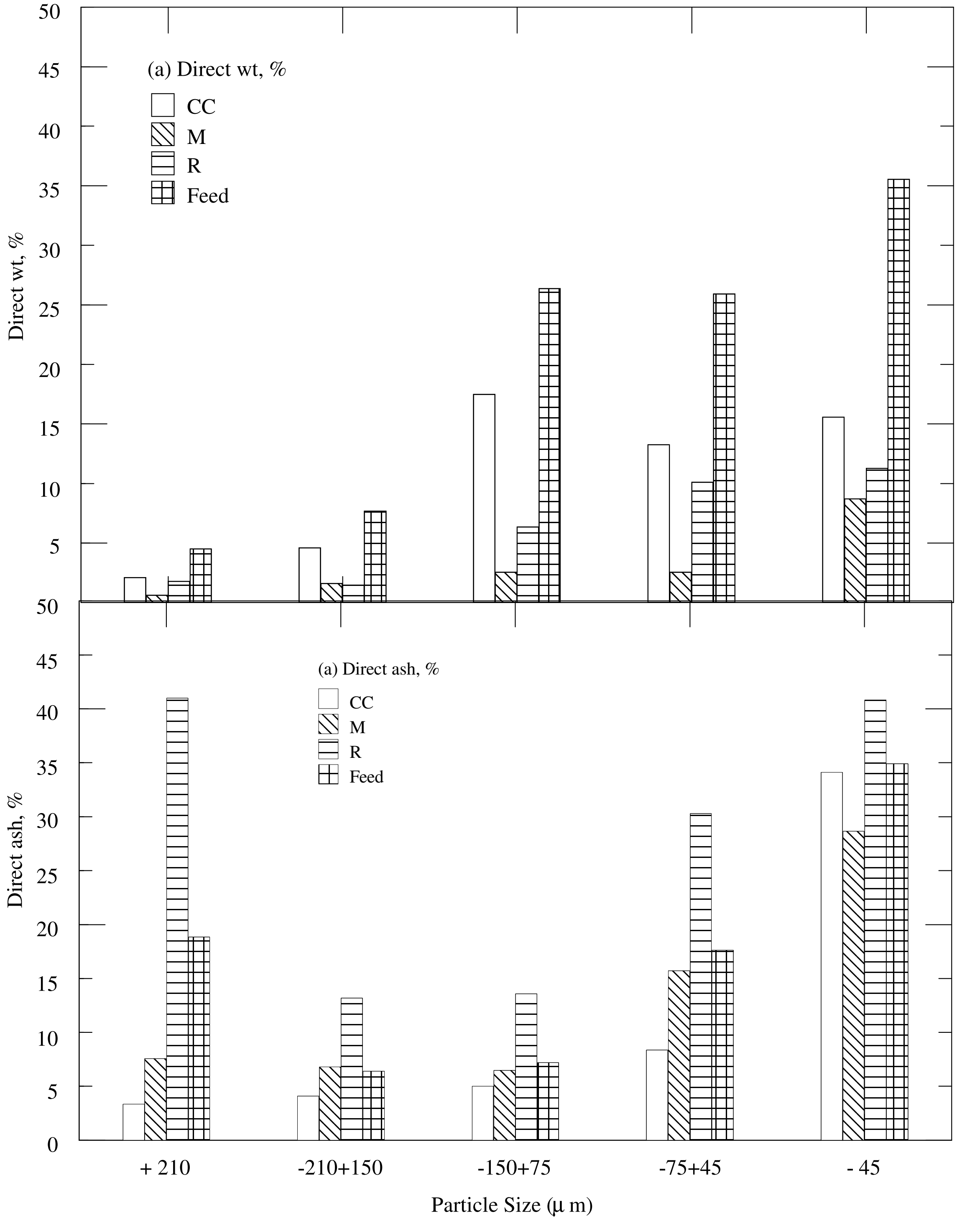

Figure 4.3 Direct weight and ash percentages of feed and products by particle size interval for ultrafine spiral: (a) Direct weight%; (b) Direct ash%

Table 4.5 Grade-yield curve calculations for reconstituted feed, and products of ultrafine spiral

	Feed				Clean Coal				Middlings				Clean Coal + Middlings				Refuse				
Specific	Direct		Cumulative		Direct		Cumulative		Direct		Cumulative		Direct		Cumulative		Direct		Cumulative		Mean
Gravity Interval	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	wt, %	ash, %	SPGR
< 1.30	36.2	4.9	36.2	4.9	25.5	4.7	25.5	4.7	4.6	5.1	4.6	5.1	30.1	4.8	30.1	4.8	6.1	5.1	6.1	5.1	1.3
1.30 - 1.40	21.0	7.9	57.2	6.0	11.2	8.7	36.6	5.9	3.8	6.3	8.4	5.6	15.0	8.1	45.1	5.9	6.0	7.4	12.1	6.3	1.4
1.40 - 1.50	8.3	15.8	65.5	7.3	4.0	15.7	40.7	6.9	1.7	17.3	10.2	7.6	5.8	16.2	50.8	7.1	2.5	15.4	14.6	7.8	1.5
1.50 - 1.60	8.5	23.6	73.9	9.1	2.8	24.1	43.4	8.0	2.0	22.7	12.2	10.1	4.8	23.5	55.6	8.5	3.7	23.3	18.3	10.9	1.6
1.60 - 1.70	8.5	32.2	82.4	11.5	5.1	32.3	48.5	10.6	0.9	33.5	13.1	11.8	6.0	32.5	61.6	10.8	2.4	31.3	20.7	13.3	1.7
1.70 - 1.80	5.2	42.2	87.6	13.3	2.3	44.7	50.9	12.1	0.9	42.4	14.1	13.8	3.3	44.0	64.9	12.5	1.9	38.0	22.6	15.4	1.8
1.80 - 1.90	2.1	50.6	89.6	14.2	0.8	55.4	51.7	12.8	0.5	45.9	14.6	15.0	1.4	51.7	66.3	13.3	0.7	45.0	23.4	16.3	1.9
1.90 - 2.00	3.3	57.4	92.9	15.7	0.5	55.7	52.2	13.2	0.4	66.6	15.0	16.5	0.9	61.0	67.2	13.9	2.4	55.5	25.7	19.9	2.0
> 2.00	7.1	80.6	100.0	20.3	0.8	79.5	53.0	14.3	1.0	77.4	16.0	20.2	1.8	78.4	69.0	15.6	5.3	84.0	31.0	30.8	2.2

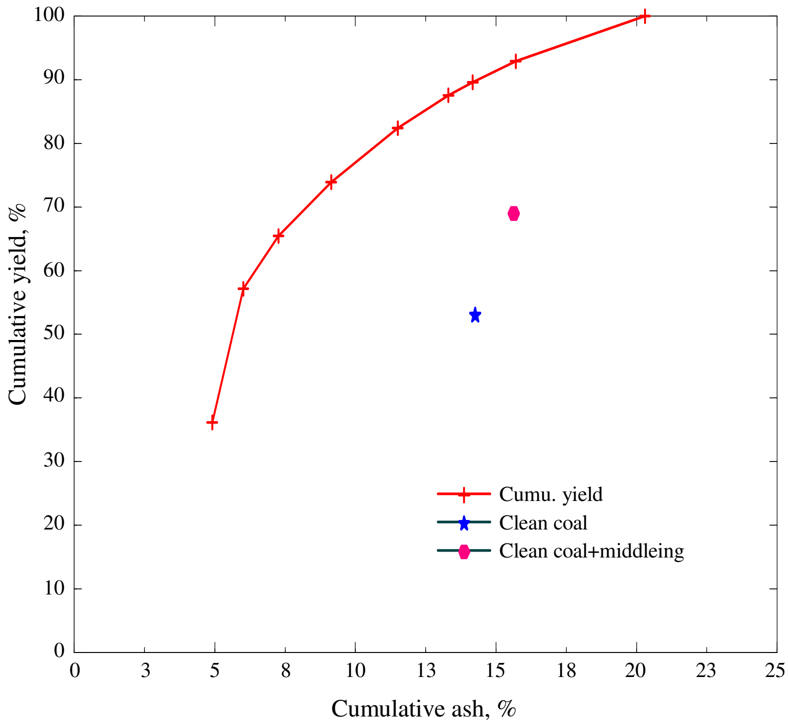

Figure 4.4 Grade-yield curve and clean coal, and clean coal+ middlings products of ultrafine spiral

4.5 Performance Separation distribution curves for ultrafine spiral

Table 4.6 and 4.7 are the performance distribution data at different particle size intervals for clean coal, clean coal+middlings, and composited samples of ultrafine spiral concentrator. Those data is obtained from float-sink test results and Eqs (3.4) and (3.5) for the products of ultrafine spiral concentrator. In Figure 4.5 to 4.13, the actual experiment data points and fitted distribution curves for the products and composite samples of ultrafine spiral at the given particle size intervals are presented. The curve fitted values are shown as lines, and actual experiment data points are shown in symbols. For better visualizing the particle size effects on the performance distribution curves, Figure 4.5 and Figure 4.9 are further divided into three separated figures in Figures 4.6, 4.7, and 4.8 for clean coal products, and Figures 4.10, 4.11, and 4.12 for clean coal+middlings products, respectively. Figures 4.11 and 4.13 shows the performance distribution factor reporting to clean coal, and clean coal+middlings for composite samples, respectively.

Under a given flowrate and solid concentration of feed for ultrafine spiral, as they demonstrate in the performance distribution curves, the feed flowrate seems high enough for separation of coarser particles size intervals, including performance distribution curve for -210+150μm size interval, a displaced particles in the feed . However, as the particle size decreases, Ep and SG values increase drastically. If the feed flowrate is getting too high, or the feed slurry is too diluted, the smaller and/or lighter particles have the tendency of floating with water causing the misplaced particles in the products.

Table 4.6 Particle size effect on clean coal distributor curves for ultrafine spiral

	a	b	c	d	e	f
SG	+210µm	-210µm+150µm	-150µm+75µm	-75µm+45µm	-45µm	Composite Sample
1.28	63.49	70.04	59.82	82.5	56.72	70.4
1.35	63.81	85.98	40.19	46.78	63.94	53.18
1.45	61.28	41.83	56.26	46.11	79.75	48.62
1.55	0	46.68	22.58	42.74	62.25	32.71
1.65	0	0	13.29	28.76	62.36	60.27
1.75	0	0	38.76	15.03	37.18	44.97
1.85	0	0	0	37.08	28.3	40.07
1.95	0	0	0	0	5.16	14.57
2.2	0	0	0	0	27.52	11.87

Table 4.7 Particle size effect on clean coal+middlings distributor curves for ultrafine spiral

	a	b	c	d	e	f
SG	+210µm	-210µm+150µm	-150µm+75µm	-75µm+45µm	-45µm	Composite Sample
1.28	82.57	94.52	75.79	96.4	82.64	83.14
1.35	81.55	95.98	59.87	86.11	94.73	71.48
1.45	74.44	81.72	67.92	83.91	93.69	69.48
1.55	16.18	62.88	43.61	66.95	91.49	56.46
1.65	27.89	22.27	26.15	79.16	95.92	71.17
1.75	0	45.25	59.08	77.57	87.3	63.35
1.85	0	0	0	68.48	78.34	65.55
1.95	0	0	0	74.33	88.81	28.28
2.2	0	0	0	30.47	63.96	25.38

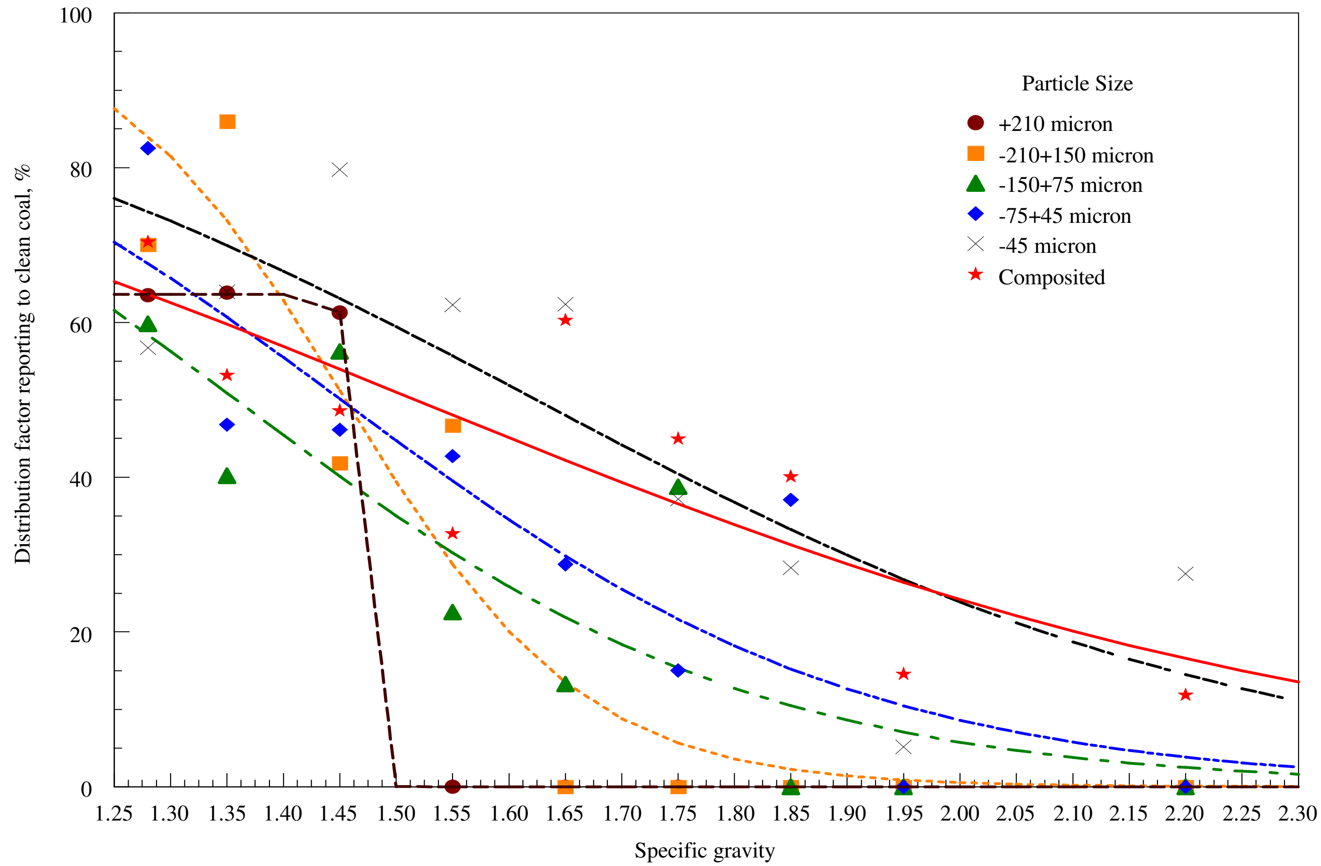

Figure 4.5 Particle size effect on performance distribution curves of clean coal products for ultrafine spiral concentrator

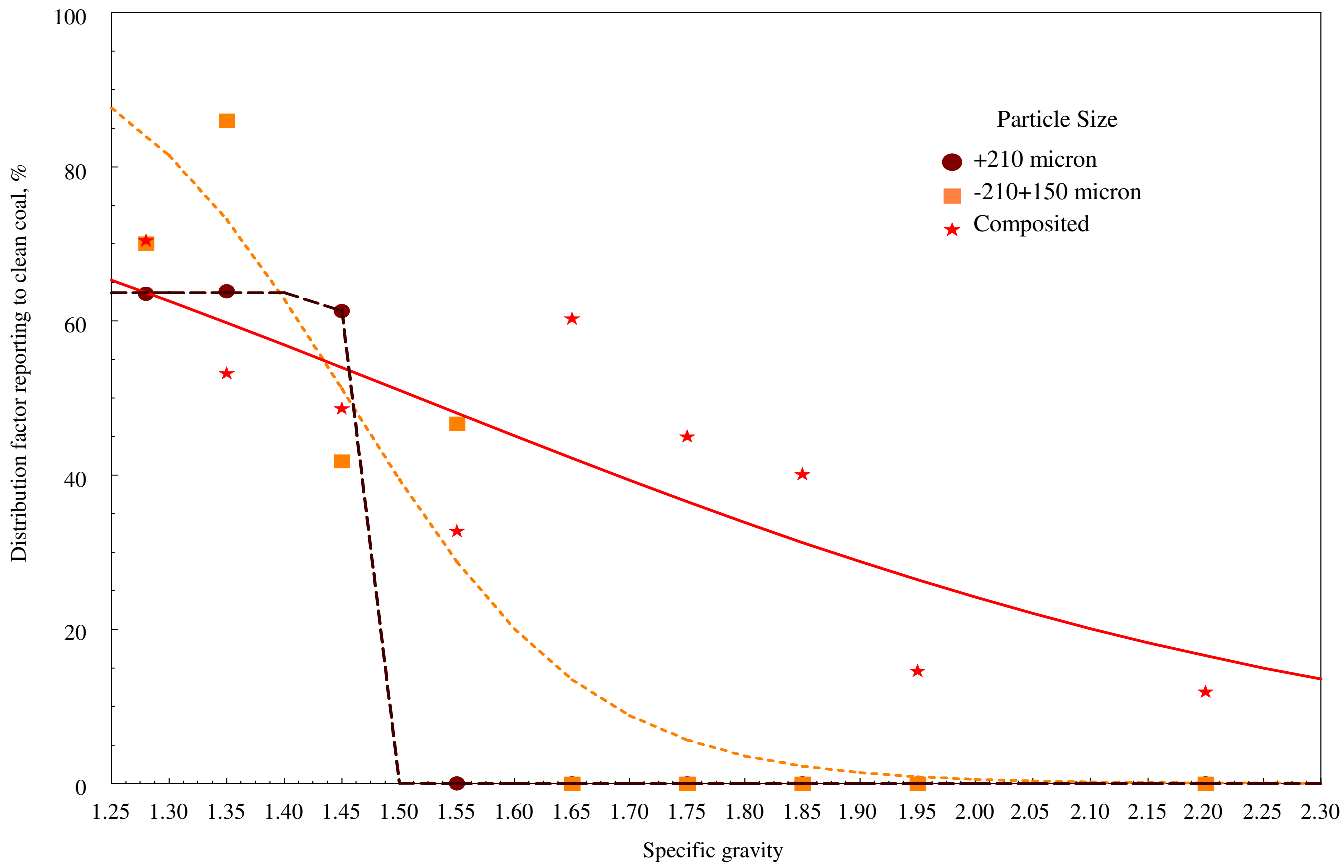

Figure 4.6 Performance distribution curves with particle size intervals for +210m; -210+150m and composite sample

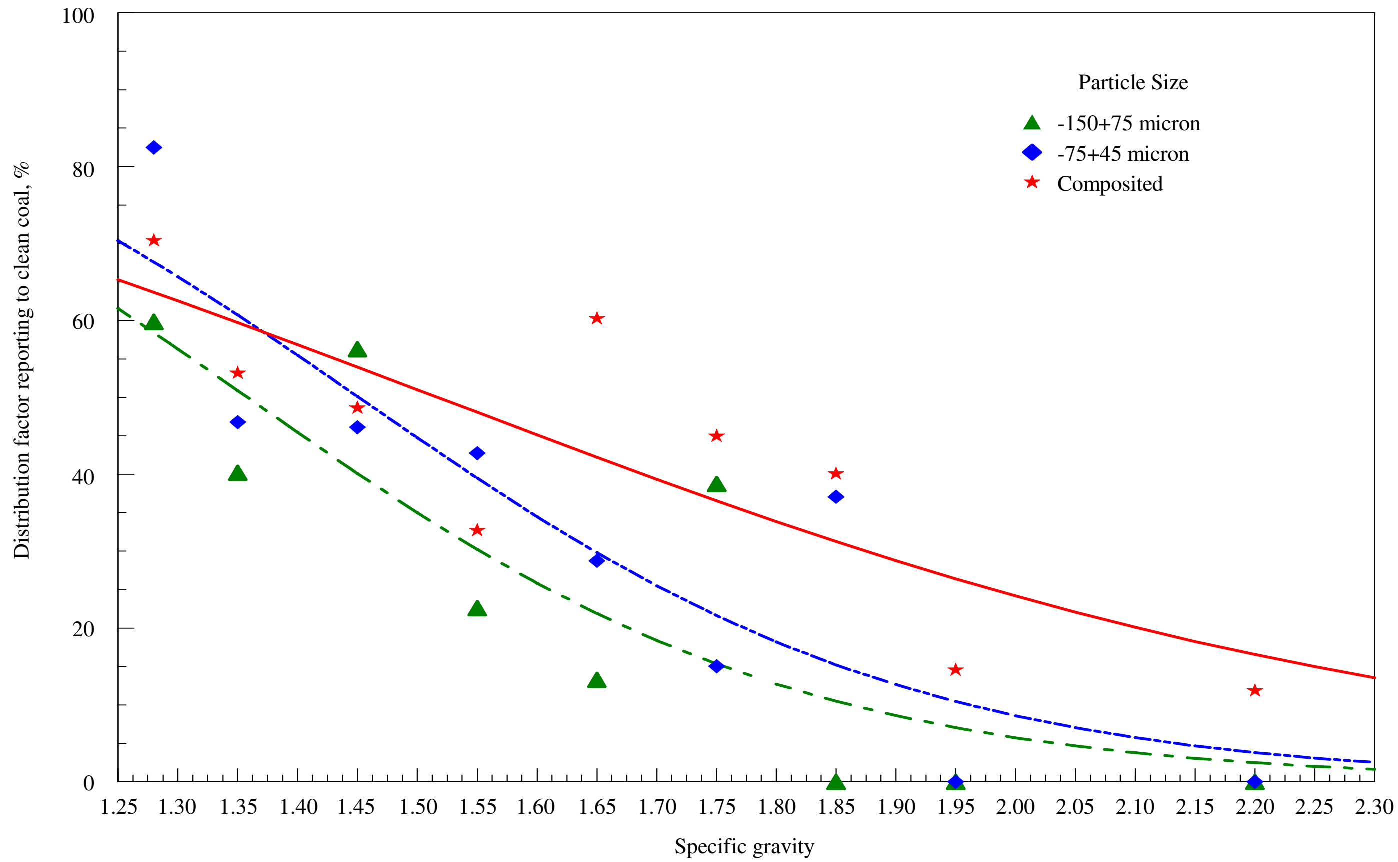

Figure 4.7 Performance distribution curves with particle size intervals for -150+75m; -75+45m; -45m and composite sample

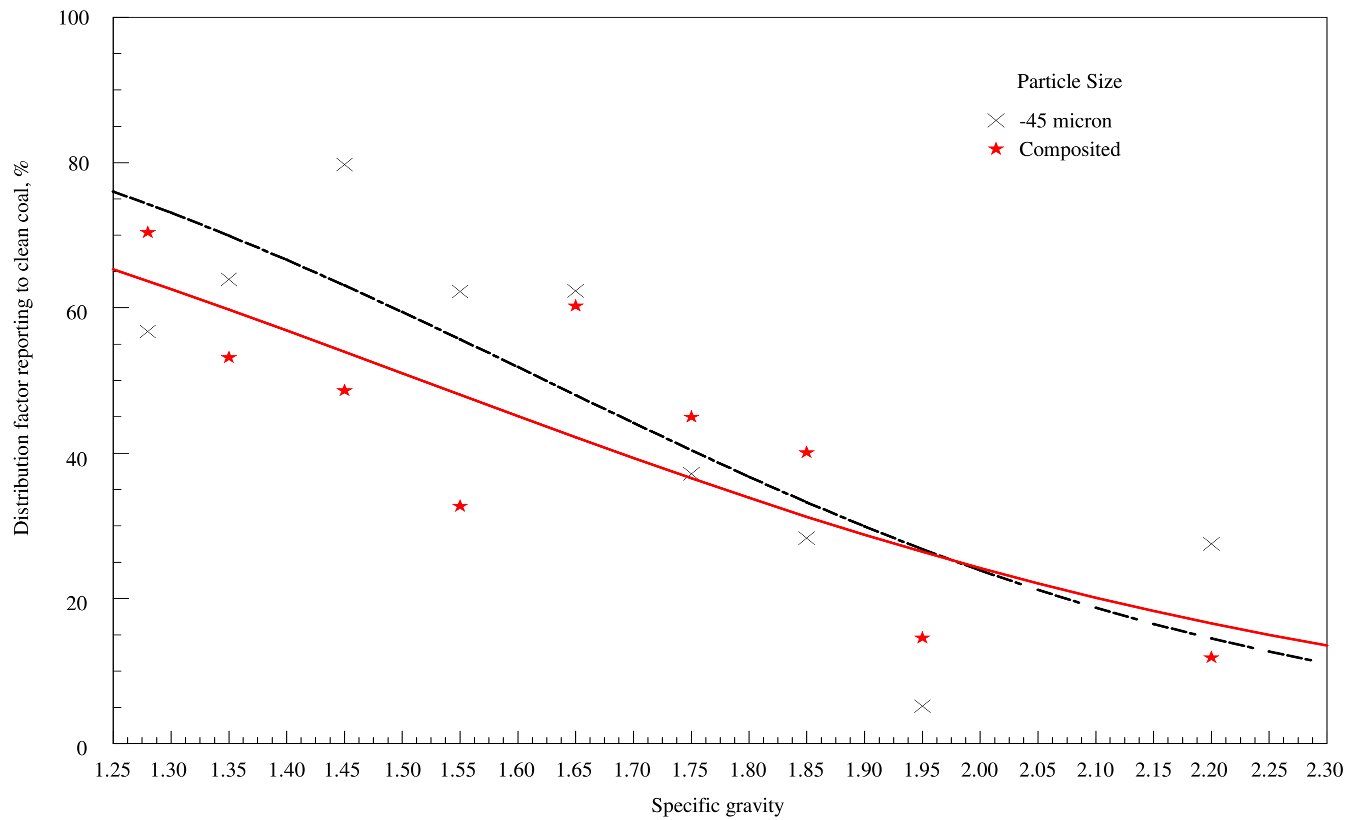

Figure 4.8 Performance distribution curves with particle size intervals for-45m and composite sample

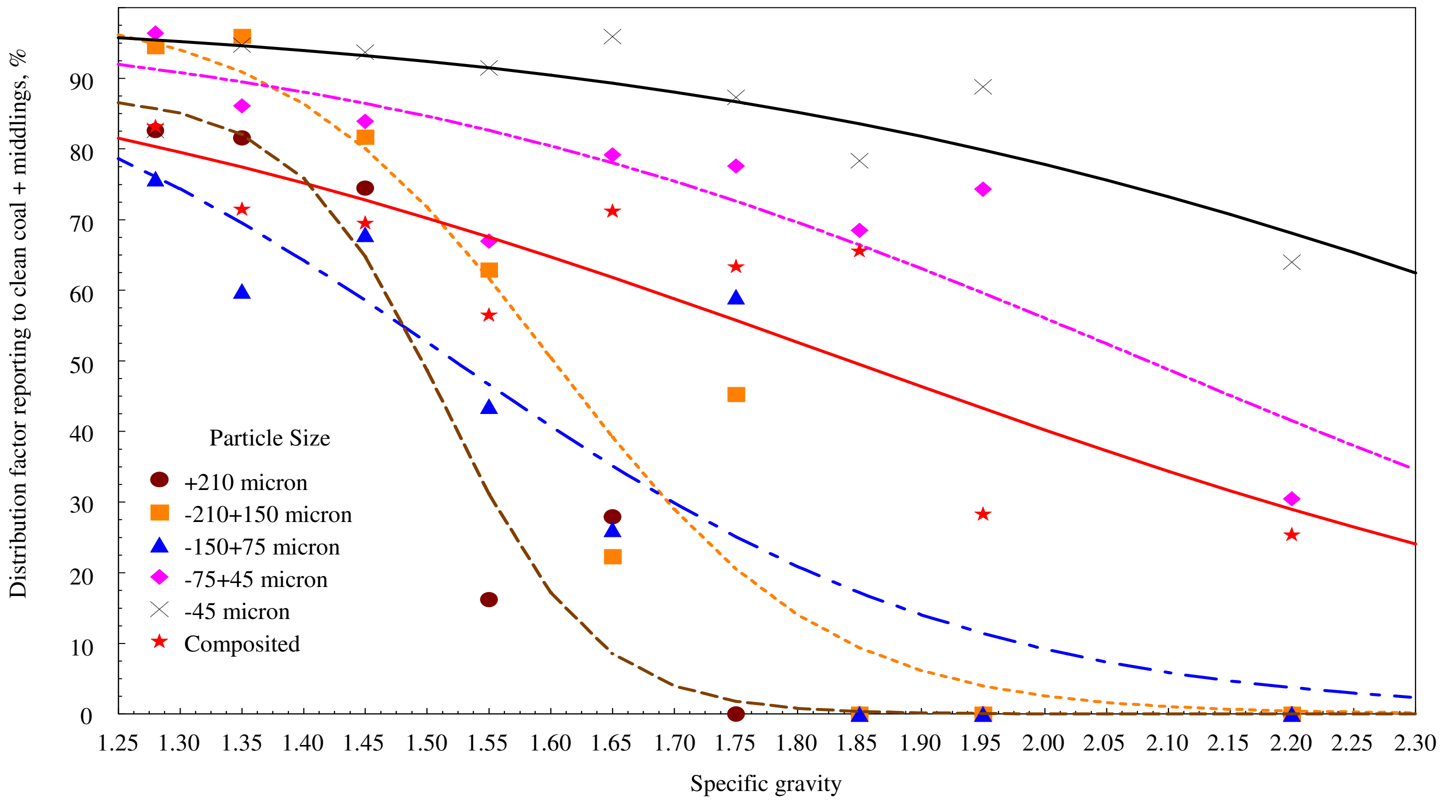

Figure 4.9 Particle size effect on performance distribution curves of clean coal+middlings products for ultrafine spiral concentrator

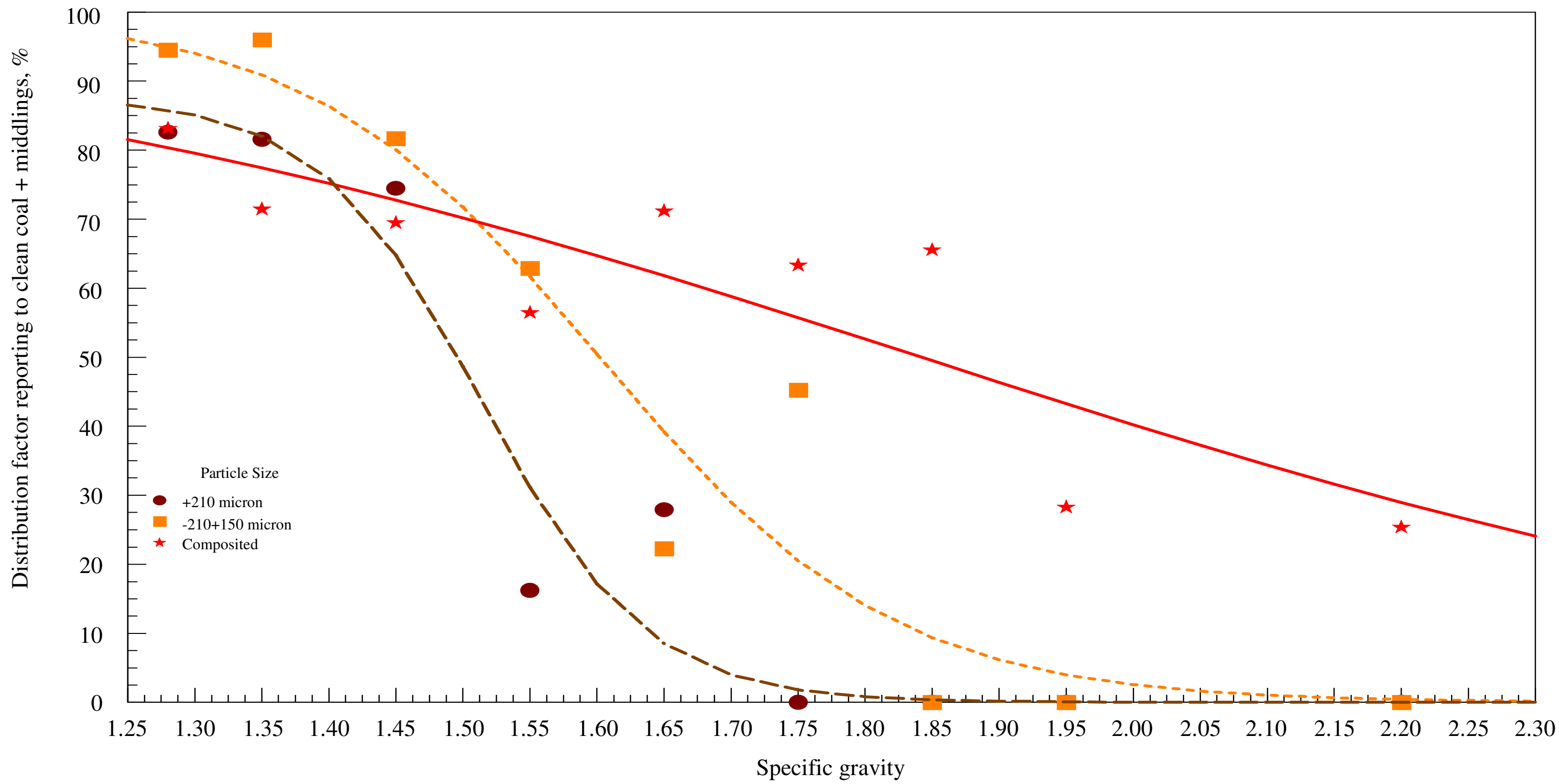

Figure 4. 10 Performance distribution curves with particle size intervals for -210m; -210+150m and composite sample

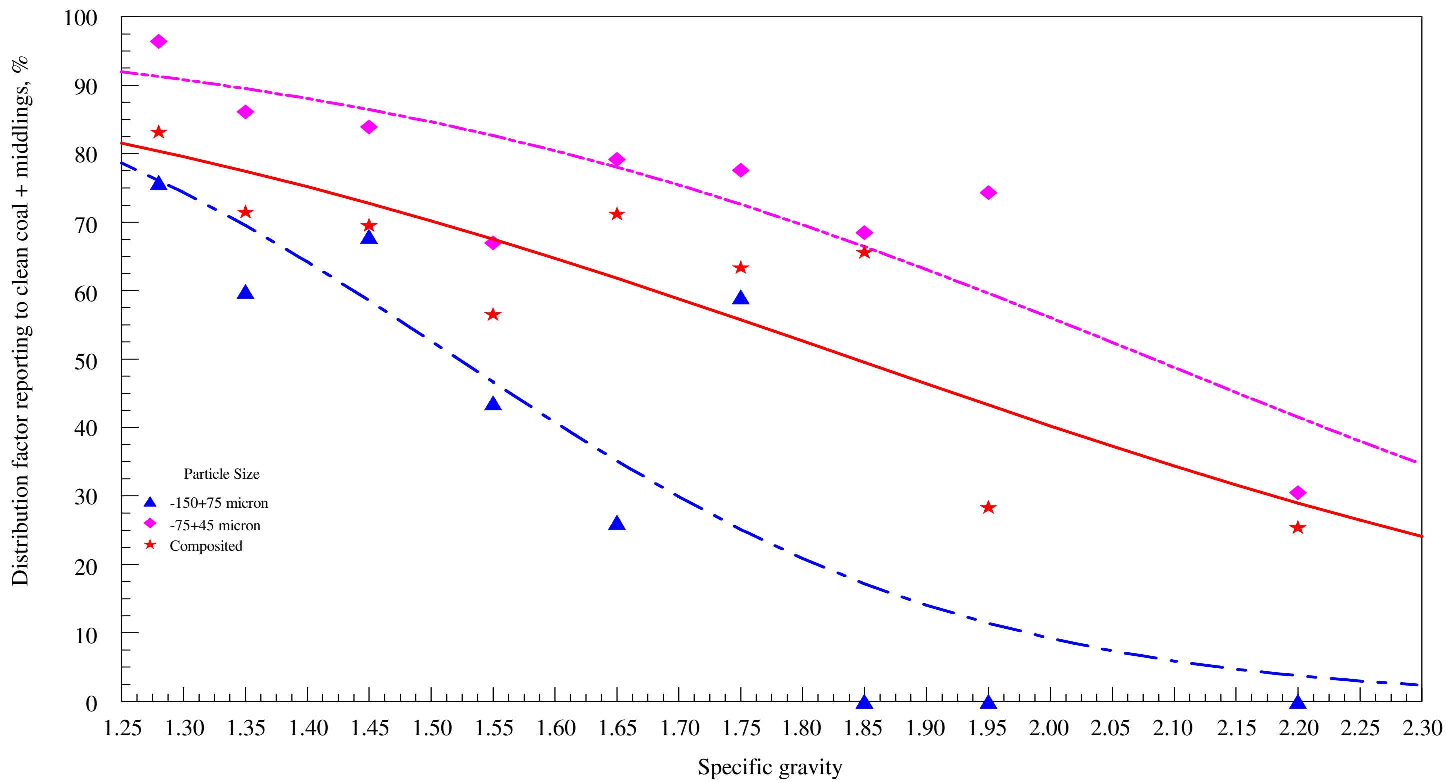

Figure 4. 11 Performance distribution curves with particle size intervals for -150+75m; -75+45m and composite sample

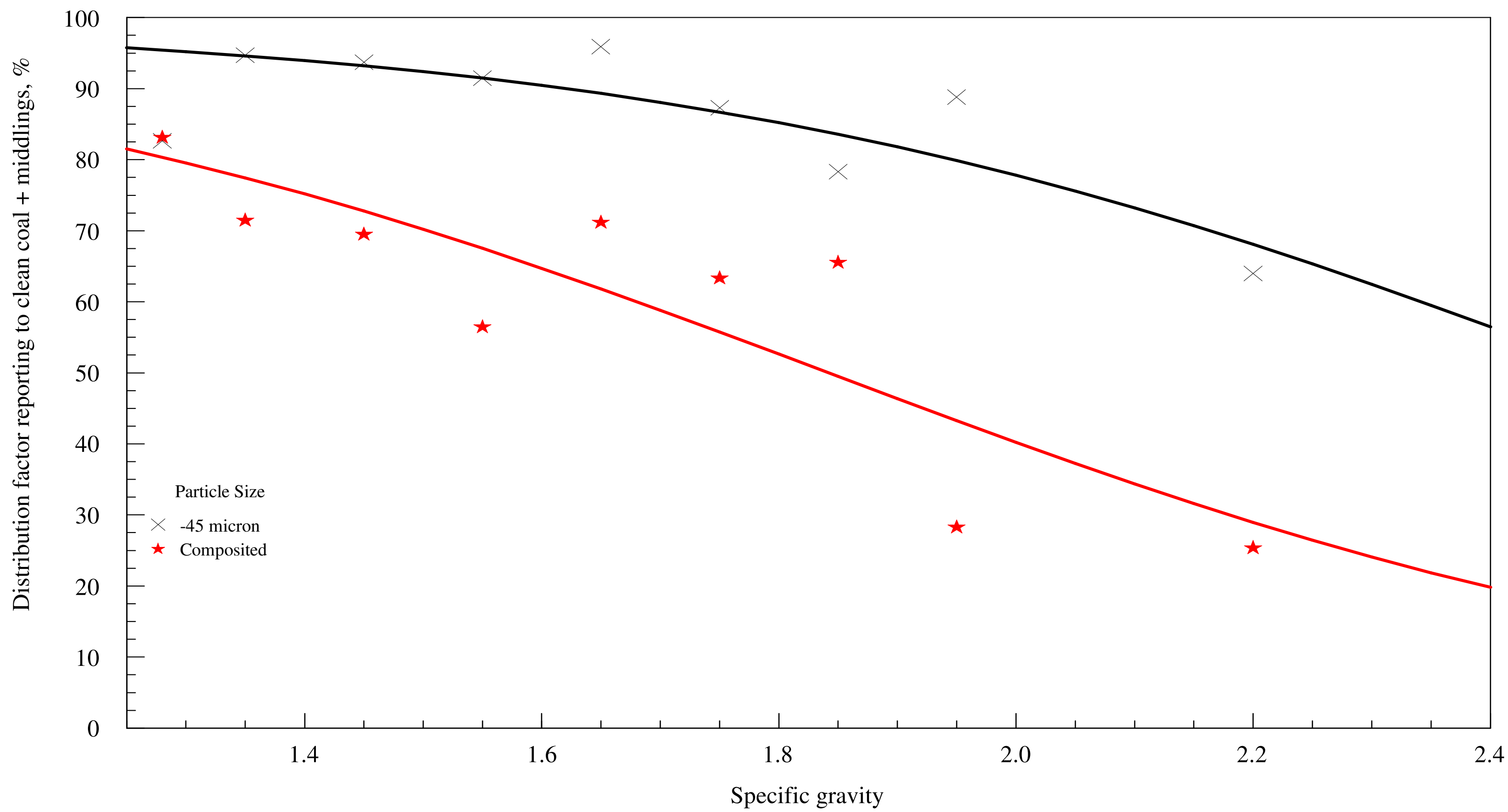

Figure 4. 12 Performance distribution curves with particle size intervals for -45m and composite sample

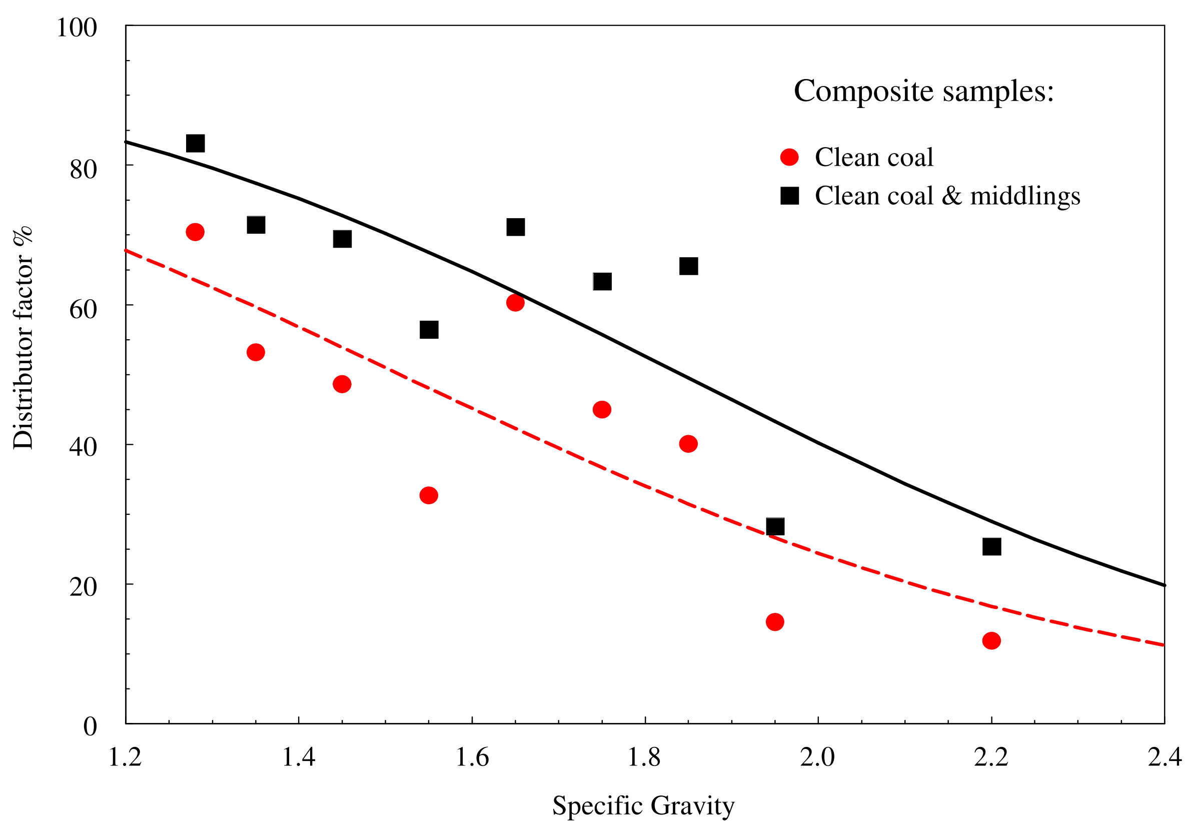

Figure 4.13 Performance distribution curves clean coal, and clean coal+middlings products for ultrafine spiral

4.6 Particle size effects on performance distribution curves of ultrafine spiral

The values of probable errors, Ep, specific gravity separation, SG50, and coefficient of variation, CV at various mean particle size are summarized in Tables 4.8 and 4.9 for clean coal, and clean coal+middlings products of ultrafine spiral concentrator. The Particle size effects on the characteristic parameters, Ep_j, $SG50_j$, and CV_j, are exhibited in Figures 4.14 and 4.15 for clean coal, and clean coal+middleings products of ultrafine spiral concentrator, respectively. The misplaced particles in feed affect the variations of Ep_j, $SG50_j$, and CV_j values, and the general trend of the correlation with mean particle sizes.

Table 4. 8 Distribution curve characteristics parameters and coefficient of variation values of clean coal products at different size intervals for ultrafine spiral

Particle Size Interval	EP	SG50	CV	Geometric Mean Particle Size
+210µm	0.005	1.464	0.003	354.965
-210µm+150µm	0.115	1.455	0.079	177.482
-150µm+75µm	0.252	1.358	0.185	106.066
-75µm+45µm	0.255	1.451	0.176	58.095
-45µm	0.356	1.624	0.219	15.000
Composite Sample	0.469	1.517	0.309	

The correlation of Ep, SG50, and CV values with geometric mean particle size are particularly useful in simulation of predicting coal cleaning results of ultrafine spiral unit operations for ultrafine coal cleaning circuit design for coal preparation plants.

As can be seen, if the particle size decreases from 150µm to 45µm or less, the Ep values decrease from 0.115 to 0.336, SG50 values increase from 1.455 to 1.642, and CV values increase from 117.48 to 15.00 for clean coal products, while the Ep values increase from 0.120 to 0.442, and SG50 values increase from 1.60 to 2.505 for clean coal+middlings products for ultrafine spiral. Very high values of Ep and SG50 for minus 45µm particles size are noticeable. This also translates to high content of ash forming materials in minus 45µm particle sizes fraction. To remediate the problem, the clean coal and clean coal middlings products require to be treated in the product classifying cyclones to deslime high ash clay particles to maintain the higher quality of the products for the ultrafine spiral concentrator. If a new ultrafine coal cleaning circuit ais under consideratuib in a new coal preparation plant, installation of more efficient smaller size of feed classifying cyclones must considered to minimum the misplaced particles in the feed for ultrafine spiral concentrator.

Table 4. 9 Distribution curve characteristics parameters and coefficient of variation values of clean coal+middlings products at different size intervals for ultrafine spiral

Particle Size Interval	EP	SG50	CV	Geometric Mean Particle Size
+210µm	0.067	1.513	0.044	354.965
-210µm+150µm	0.120	1.602	0.075	177.482
-150µm+75µm	0.229	1.522	0.150	106.066
-75µm+45µm	0.375	2.083	0.180	58.095
-45µm	0.442	2.505	0.176	15.000
Composite Sample	0.438	1.842	0.238	

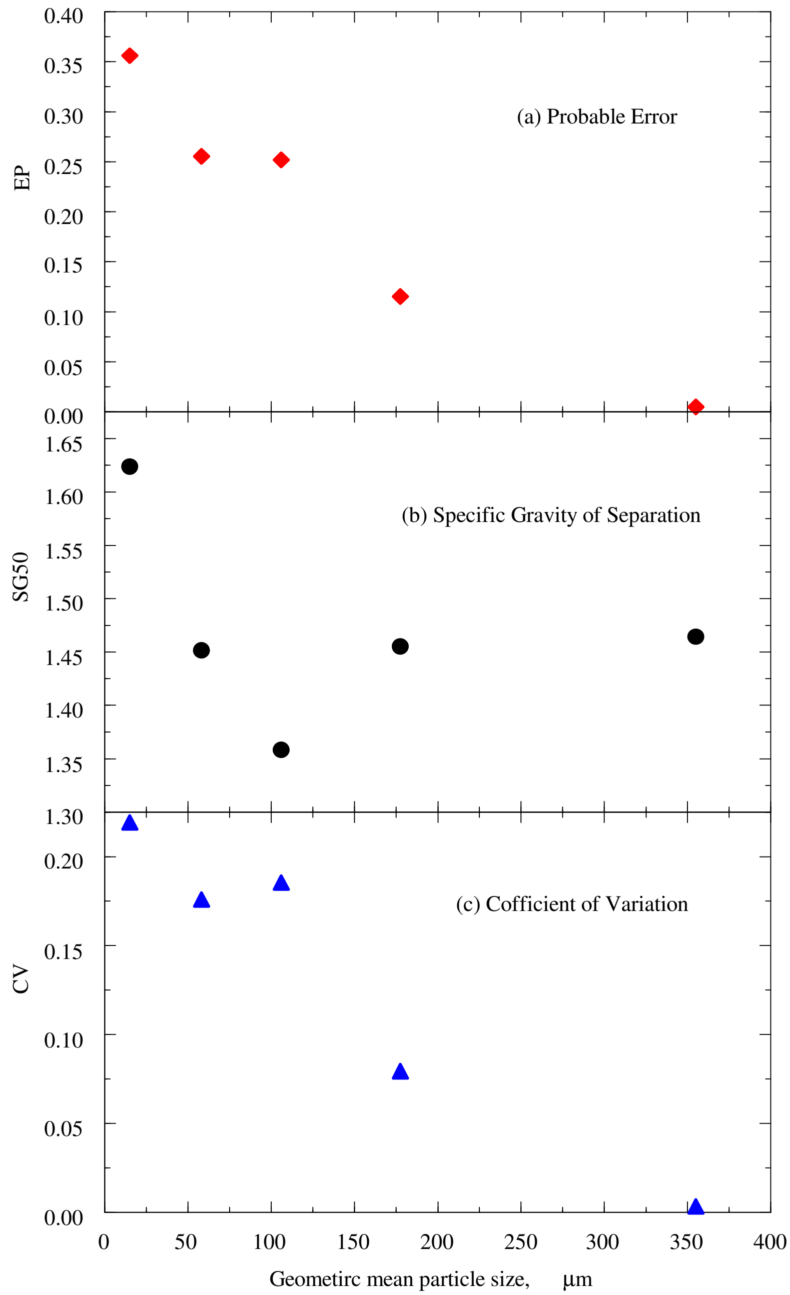

Figure 4.14 Performance distribution characteristic parameters of clean coal as a function of particle size for ulrafine spiral concentrator: (a) Ep; (b) SG50; and (c) CV

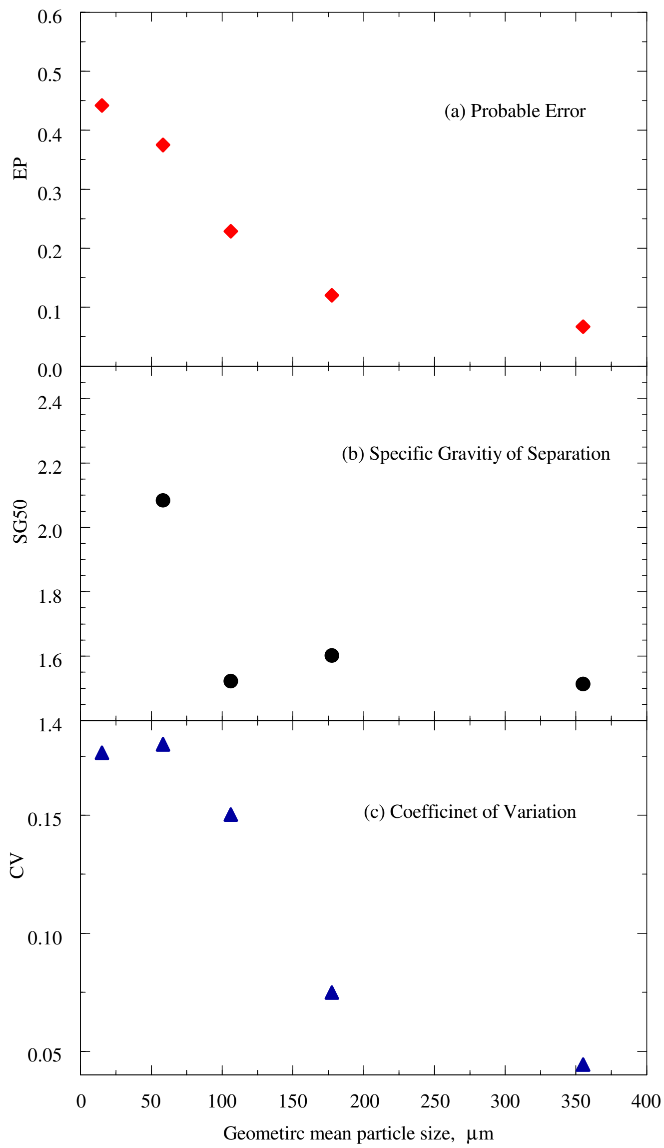

Figure 4.15 Performance distribution parameters as function of particle size for clean coal+middlings of ulrafine spiral concentrator: (a) Ep; (b) SG50; and (c) CV.

CHAPTER 5 CONCLUSIONS

1) Combined four and three short turns two-staged spirals have been used in ultrafine coal cleaning circuit to treat the particle sizes interval of -150+ 45µm raw ultrafine coal. Despite of large quantities of misplaced particles from the inefficiency of classifying cyclones upstream, the ultrafine spiral is capable of separation of ultrafine raw coal relatively effective.

2) Despite of using desliming secondary classifying cyclone to removal of minus 45 µm particles from overflow of primary cyclone (feed to ultrafine spiral), the large quantity of high ash clay particles in minus 45 µm are misplaced placed in the feed for ultrafine spiral. Those high ash particles are detrimental to the qualities of clean coal and clean coal+middling products for ultrafine spiral. One of the remediation methods is to deslime minus 45µm particles from clean coal and midllings products using product classifying cyclones after coal cleaning in an existing coal preparation plant. For a new coal preparation plant, higher efficiency small size classifying cyclones might need to consider for preparation of feed for ultrafine spiral.

3) From the study of particle size effects on performance distribution curves and characteristic parameters, the large changes in the efficiency of ultrafine coal separation as the particle size decreasing under a given flowrate and solid concentration in feed to produce clean coal and middlings products is observed. A

narrower feed size might be more desirable for ultrafine spiral separation, by using appropriate operation conditions for the narrower particle size interval.

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APPENDIX A

LABOROTORY OPERATING PROCEDURES

A-1 WET SIEVING PROCEDURE

1. To prepare for a wet sieve tests, place wet coal samples in the large coal sample trays and into an large air venting draft oven. The coal samples are dried at 50^{o} C until reached a constant mass.
2. Weigh an appropriate amount of coal samples to the nearest 0.1 g.
3. When the weighted coal sample is readily to be mixed with water, place the coal sample on the coarsest sieve of a series of selected sieves, and wash the sieve back and forth over the coal sample with a gentle stream of water from a garden hose. The sieve is placed on the vibrating sieve shaker.
4. When the water passing through the sieve is clear, place the sample passed through the coarsest sieve on the second coarser sieve until pass through the finest sieve.
5. Dry the sieve with wet coal sample in a draft oven at 50°C for 12 hours or until the constant mass is reached.
6. Weigh the coal sample from each sieve, bag, label and store in a freezer.

A-2 FLOAT-SINK ANALYSIS PROCEDURE

1. The coal sample bag is removed from the freezer. The necessary amount of coal sample is dried, splitted, and weighed (see Step 4) each representative sample for float-sink tests.
2. In an analytical or industrial ventilation hood, dilute Lithium Metatungstate heavy liquid (LMT) with distilled water in 4000 ml beakers to prepare LMT heavy liquid in following specific gravities: 1.30, 1.40, 1.50, 1.60, 1.70, 1.80, 1.90 and 2.00 and 2.50.
3. Then, each prepared LMT liquid is poured into a 1000 ml pear shaped separatory funnel. The remaining heavy liquid is poured into an appropriated bottled with cap.
4. Measure each specific gravity of the heavy liquid by using a hydrometer prior to float-sink test.
5. Weigh the amount of coal sample that would yield a solid concentration of no more than 5% by volume.
6. Place the pre-weighed coal samples into prepared LMT solution in a 1000 ml separatory funnel with stopcock closed.
7. Manually stirring the liquid and coal sample by a glass rod to ensure that all of the coal is wetted.
8. Use wash bottle to wash the stirring rod and the inside walls of the separator.

9. Cover the separator with paraffin film to minimize evaporation of liquid and leaving solids to sit for at least 12 hours.

10. After the separation is completed, the sink material is drained off from the separatory funnel by opening the stopcock slowly. Place sink material in a filter labeled as “Sink”, and pour the float material remained in the separatory funnel in a filter labeled as “Float”. Drain LMT liquid and filtrates, and returning them into the appropriate bottles.

11. Dry both float and sink materials into draft oven at 40^{o}C to ensure that all the surface liquid is dried.

12. After 12 hours in the draft oven, take both coal samples out of the oven, and weigh and bag and stored in a deccicator for subsequent analysis.

A-3 ASH ANALYSIS PROCEDURE

1. Coal samples are prepared to minus 250 μm by passing through Holms mill according to ASTM method specified.
2. Transfer 1 gram of coal sample to a weighed capsule and cover quickly and store into a dessicator.
3. Place the capsules in a cold muffle furnace and heat gradually at a rate that the temperature reaches 450^{o} C - 500^{o}C in one hour. Open the furnace door ajar by using a steel bar (Steps 3 to 5 are automatic programmed).
4. Continue heating to 750^{o}C is reached by the end of the second hour.
5. At the end of 4 hours, switch off the furnace automatically. Continue ashing overnight for completed combustion.
6. Remove the capsule from the muffle furnace, and place the capsule in an dessicator to cool down.
7. After the coal samples reach the room temperature, weigh the residue materials in the capsules. Record the weighs.

APPENDIX B

Particle size distribution data and analysis

Table 4.1 Fine Spiral Clean Coal Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No.10	3.20	0.64
-2000+1680	-No. 10 +No. 12	9.40	1.88
-1680+1400	-No. 12 +No. 16	64.20	12.82
-1400+1000	-No. 16 +No. 18	48.40	9.67
-1000+600	-No. 18 + No. 30	139.40	27.84
-600+250	-No. 30 +No. 60	131.50	26.26
-250+150	-No. 60 +No. 100	47.50	9.49
-150	-No. 100	57.10	11.40
	Total	500.70	100.00

Table 4.2 Fine Spiral Middling Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No.10	3.00	0.60
-2000+1680	-No. 10 +No. 12	11.60	2.30
-1680+1400	-No. 12 +No. 16	58.30	11.58
-1400+1000	-No. 16 +No. 18	40.70	8.08
-1000+600	-No. 18 + No. 30	106.30	21.11
-600+250	-No. 30 +No. 60	181.00	35.94
-250+150	-No. 60 +No. 100	52.90	10.50
-150	-No. 100	49.80	9.89
	Total	503.60	100.00

Table 4.3 Fine Spiral Refuse Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No.10	1.70	0.34
-2000+1680	-No. 10 +No. 12	4.80	0.95
-1680+1400	-No. 12 +No. 16	34.20	6.80
-1400+1000	-No. 16 +No. 18	30.00	5.96
-1000+600	-No. 18 + No. 30	120.20	23.88
-600+250	-No. 30 +No. 60	184.00	36.56
-250+150	-No. 60 +No. 100	62.30	12.38
-150	-No. 100	66.10	13.13
	Total	503.30	100.00

Table 4.5 Utrafine Spiral Clean coal Product

Size(μm)	U.S. Sieve Series	Weight (g)	Wt (%)
+600	+No.30	0.70	0.29
-600+250	-No. 30 +No. 60	4.70	1.95
-250+210	-No. 60 +No. 70	5.70	2.36
-210+150	-No. 70 +No. 100	24.10	9.98
-150+75	-No. 100 + No. 200	79.60	32.95
-75+45	-No. 200 +No. 325	60.60	25.09
-45	-No. 325	66.15	27.39
	Total	241.55	100.00

Table 4.6 Utrafine Spiral Spiral Middling Product

Size(μm)	U.S. Sieve Series	Weight (g)	Wt (%)
+600	+No.30	0.70	0.28
-600+250	-No. 30 +No. 60	4.70	1.91
-250+210	-No. 60 +No. 70	4.30	1.75
-210+150	-No. 70 +No. 100	33.60	13.65
-150+75	-No. 100 + No. 200	3.00	1.22
-75+45	-No. 200 +No. 325	8.40	3.41
-45	-No. 325	191.52	77.78
	Total	246.22	100.00

Table 4.7 Utrafine Spiral Refuse Product

Size(μm)	U.S. Sieve Series	Weight (g)	Wt (%)
+600	+No.30	3.10	1.26
-600+250	-No. 30 +No. 60	6.70	2.72
-250+210	-No. 60 +No. 70	2.90	1.18
-210+150	-No. 70 +No. 100	13.90	5.64
-150+75	-No. 100 + No. 200	44.60	18.09
-75+45	-No. 200 +No. 325	71.20	28.88
-45	-No. 325	104.12	42.24
	Total	246.52	100.00

APPENDIX C

WASHABILITY DATA ANALYSIS

Table 4.9 Fine Spiral Clean Coal Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No. 18	233.00	23.38
-2000+1680			
-1680+1400			
-1400+1000			
-1000+600	-No. 18 + No. 30	271.00	27.19
-600+250	-No. 30 +No. 60	276.60	27.75
-250+150	-No. 60 +No. 100	98.60	9.89
-150	-No. 100	117.50	11.79
	Total	996.70	100.00

Table 4.10 Fine Spiral Middling Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No. 18	216.50	21.37
-2000+1680			
-1680+1400			
-1400+1000			
-1000+600	-No. 18 + No. 30	228.20	22.53
-600+250	-No. 30 +No. 60	346.30	34.19
-250+150	-No. 60 +No. 100	108.60	10.72
-150	-No. 100	113.40	11.19
	Total	1013.00	100.00

Table 4.11 Fine Spiral Refuse Product Sieving Results

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+2000	+No. 18	145.40	14.45
-2000+1680			
-1680+1400			
-1400+1000			
-1000+600	-No. 18 + No. 30	236.80	23.53
-600+250	-No. 30 +No. 60	370.10	36.77
-250+150	-No. 60 +No. 100	121.00	12.02
-150	-No. 100	133.20	13.23
	Total	1006.50	100.00

Table 4.12 Utrafine Spiral Clean coal Product

Size(µm)	U.S. Sieve Series	Weight (g)	Wt (%)
+600			
-600+250	+No. 70		
-250+210		19.29	3.96
-210+150	-No. 70 +No. 100	42.20	8.67
-150+75	-No. 100 + No. 200	160.50	32.99
-75+45	-No. 200 +No. 325	121.70	25.01
-45	-No. 325	142.85	29.36
	Total	486.54	100.00

Table 4.13 Utrafine Spiral Middling Product

Size(µm)	U.S. Sieve Series	Weight,(g)	Wt, (%)
+600	+No.30		
-600+250	-No. 30 +No. 60		
-250+210	-No. 60 +No. 70	20.70	3.82
-210+150	-No. 70 +No. 100	54.40	10.04
-150+75	-No. 100 + No. 200	85.80	15.84
-75+45	-No. 200 +No. 325	86.30	15.93
-45	-No. 325	294.39	54.36
	Total	541.59	100.00

Table 4.14 Utrafine Spiral Refuse Product

Size(µm)	U.S. Sieve Series	Weight,(g)	Wt, (%)
+600	+No.30		
-600+250	-No. 30 +No. 60		
-250+210	-No. 60 +No. 70	28.30	5.76
-210+150	-No. 70 +No. 100	23.50	4.78
-150+75	-No. 100 + No. 200	100.70	20.50
-75+45	-No. 200 +No. 325	160.10	32.60
-45	-No. 325	178.52	36.35
	Total	491.12	100.00

Table 1-1 Analysis of Fine Spiral Clean Coal(Size Range:+1000μm, r_1=0.2338)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_1 * Wt%
<1.30	116.05	50.43	3.53	11.79
1.30-1.40	67.65	29.40	7.23	6.87
1.40-1.50	19.79	8.60	15.49	2.01
1.50-1.60	8.11	3.52	23.13	0.82
1.60-1.70	6.08	2.64	35.15	0.62
1.70-1.80	1.58	0.69	40.52	0.16
1.80-1.90	1.58	0.69	46.77	0.16
1.90-2.00	0.81	0.35	54.4	0.08
>2.00	8.47	3.68	83.51	0.86
	230.12	100.00		

Table 1-2 Analysis of Fine Spiral Clean Coal(Size Range:-1000μm+600μm,r_2=0.2719)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_2 * Wt%
<1.30	156.73	58.47	2.7	15.90
1.30-1.40	77.08	28.76	6.35	7.82
1.40-1.50	20.98	7.83	14.07	2.13
1.50-1.60	6.54	2.44	22.13	0.66
1.60-1.70	4.00	1.49	30.73	0.41
1.70-1.80	1.17	0.44	44.36	0.12
1.80-1.90	0.49	0.18	51.57	0.05
1.90-2.00	0.14	0.05	80.67	0.01
>2.00	0.92	0.34	80.67	0.09
	268.05	100.00		

Table 1-3 Analysis of Fine Spiral Clean Coal(Size Range:-600μm+250μm,r_3=0.2775)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_3 * Wt%
<1.30	117.25	43.03	2.04	11.94
1.30-1.40	128.49	47.15	6.11	13.08
1.40-1.50	19.81	7.27	13.65	2.02
1.50-1.60	3.45	1.27	23.67	0.35
1.60-1.70	1.32	0.48	26.87	0.13
1.70-1.80	1.64	0.60	34.53	0.17
1.80-1.90	0.54	0.20	67.04	0.05
1.90-2.00				0.00
>2.00				0.00
	272.50	100.00		

Table 1- 4 Analysis of Fine Spiral Clean Coal(Size Range:-250μm+150μm,r4=0.0989)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_4 * Wt%
<1.30	36.47	38.24	2.60	3.78
1.30-1.40	49.56	51.97	5.39	5.14
1.40-1.50	4.81	5.04	14.48	0.50
1.50-1.60	1.62	1.70	22.41	0.17
1.60-1.70	0.63	0.66	29.60	0.07
1.70-1.80	1.49	1.56	35.04	0.15
1.80-1.90	0.79	0.83	67.00	0.08
1.90-2.00	0.00	0.00		0.00
>2.00	0.00	0.00		0.00
	95.37	100.00		

Table 1- 5 Analysis of Fine Spiral Clean Coal(Size Range:-150μm,r_4=0.1179)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_5* Wt%
<1.30	52.75	47.14	7.11	5.56
1.30-1.40	22.41	20.03	6.82	2.36
1.40-1.50	12.42	11.10	12.05	1.31
1.50-1.60	5.02	4.49	17.78	0.53
1.60-1.70	7.90	7.06	25.69	0.83
1.70-1.80	1.43	1.28	37.14	0.15
1.80-1.90	0.55	0.49	51.60	0.06
1.90-2.00	0.43	0.38	55.37	0.05
>2.00	8.98	8.03	80.94	0.95
	111.89	100.00		

Table 1 Analysis of Fine Spiral Clean Coal(0.53)

Specific Gravity Interval	Direct	
	wt%	Ash%
< 1.30	48.97	3.23
1.30 - 1.40	35.28	6.32
1.40 - 1.50	7.96	14.02
1.50 - 1.60	2.54	21.78
1.60 - 1.70	2.06	29.73
1.70 - 1.80	0.75	37.99
1.80 - 1.90	0.41	54.89
1.90 - 2.00	0.14	57.34
> 2.00	1.90	82.09
Total	100.00	

Table 2-1 Analysis of Fine Spiral Middling(Size Range:+1000μm, r_1=0.2137)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_1 * Wt%
<1.30	14.07	6.53	11.52	1.39
1.30-1.40	17.17	7.96	8.66	1.70
1.40-1.50	10.59	4.91	16.53	1.05
1.50-1.60	11.37	5.27	31.40	1.13
1.60-1.70	10.89	5.05	36.12	1.08
1.70-1.80	10.16	4.71	42.33	1.01
1.80-1.90	9.80	4.55	47.32	0.97
1.90-2.00	10.78	5.00	54.66	1.07
>2.00	120.77	56.02	83.99	11.97
	215.60	100.00		

Table 2-2 Analysis of Fine Spiral Middling(Size Range:-1000μm+600μm,r_2=0.2253)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_2 * Wt%
<1.30	67.52	30.29	7.93	6.82
1.30-1.40	25.37	11.38	8.84	2.56
1.40-1.50	33.73	15.13	17.51	3.41
1.50-1.60	16.75	7.51	25.83	1.69
1.60-1.70	15.02	6.74	31.91	1.52
1.70-1.80	31.54	14.15	44.71	3.19
1.80-1.90	0.77	0.35	59.11	0.08
1.90-2.00	0.51	0.23	53.36	0.05
>2.00	31.72	14.23	81.57	3.21
	222.93	100.00		

Table 2-3 Analysis of Fine Spiral Middling(Size Range:-600μm+250μm,r_3=0.3419)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_3 * Wt%
<1.30	114.19	33.88	2.03	11.58
1.30-1.40	64.61	19.17	7.43	6.55
1.40-1.50	92.18	27.35	12.44	9.35
1.50-1.60	43.49	12.90	26.75	4.41
1.60-1.70	3.65	1.08	28.68	0.37
1.70-1.80	4.49	1.33	40.04	0.46
1.80-1.90	2.63	0.78	48.40	0.27
1.90-2.00	3.79	1.12	51.37	0.38
>2.00	8.04	2.39	75.12	0.82
	337.07	100.00		

Table 2- 4 Analysis of Fine Spiral Middling(Size Range:-250μm+150μm,r4=0.1072)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_4 * Wt%
<1.30	51.25	48.58	5.91	5.21
1.30-1.40	22.04	20.89	6.49	2.24
1.40-1.50	18.02	17.08	17.46	1.83
1.50-1.60	1.51	1.43	24.63	0.15
1.60-1.70	4.64	4.40	33.73	0.47
1.70-1.80	0.54	0.51	42.85	0.05
1.80-1.90	1.06	1.00	47.70	0.11
1.90-2.00	1.25	1.18	50.93	0.13
>2.00	5.18	4.91	77.80	0.53
	105.49	100.00		

Table 2- 5 Analysis of Fine Spiral Middling(Size Range:-150μm,r_4=0.1119)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_5* Wt%
<1.30	41.40	36.84	7.58	4.12
1.30-1.40	18.53	16.49	7.71	1.85
1.40-1.50	3.73	3.32	13.59	0.37
1.50-1.60	4.05	3.60	27.01	0.40
1.60-1.70	7.30	6.50	29.00	0.73
1.70-1.80	3.31	2.95	39.75	0.33
1.80-1.90	1.67	1.49	52.11	0.17
1.90-2.00	11.97	10.65	75.19	1.19
>2.00	20.42	18.17	80.28	2.03
	112.38	100.00		

Table 2 Analysis of Fine Spiral Middlings(0.16)

Specific Gravity Interval	Direct	
	wt%	Ash%
< 1.30	29.13	5.35
1.30 - 1.40	14.90	7.71
1.40 - 1.50	16.01	14.39
1.50 - 1.60	7.79	27.19
1.60 - 1.70	4.17	32.41
1.70 - 1.80	5.03	43.47
1.80 - 1.90	1.59	48.60
1.90 - 2.00	2.82	62.69
> 2.00	18.55	82.70
Total	100.00	

Table 3-1 Analysis of Fine Spiral Refuse(Size Range:+1000µm, r_1=0.1445)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_1 * Wt%
<1.30	6.14	4.27	6.86	0.62
1.30-1.40	2.22	1.54	15.79	0.22
1.40-1.50	1.44	1.00	15.83	0.14
1.50-1.60	1.03	0.72	13.34	0.10
1.60-1.70	2.08	1.45	22.24	0.21
1.70-1.80	1.18	0.82	29.80	0.12
1.80-1.90	1.87	1.30	58.43	0.19
1.90-2.00	2.76	1.92	45.91	0.28
>2.00	125.21	86.99	82.56	12.57
	143.93	100.00		

Table 3-2 Analysis of Fine Spiral Refuse(Size Range:-1000µm+600µm,r_2=0.2353)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_2 * Wt%
<1.30	18.40	7.92	45.55	1.86
1.30-1.40	6.61	2.85	13.66	0.67
1.40-1.50	6.43	2.77	17.81	0.65
1.50-1.60	4.65	2.00	29.10	0.47
1.60-1.70	7.95	3.42	34.96	0.81
1.70-1.80	3.52	1.52	40.92	0.36
1.80-1.90	5.76	2.48	49.22	0.58
1.90-2.00	4.88	2.10	52.38	0.49
>2.00	174.03	74.94	85.74	17.63
	232.23	100.00		

Table 3-3 Analysis of Fine Spiral Refuse(Size Range:-600µm+250µm,r_3=0.3677)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_3 * Wt%
<1.30	37.43	10.28	27.59	3.78
1.30-1.40	23.90	6.57	8.89	2.41
1.40-1.50	24.26	6.67	16.32	2.45
1.50-1.60	9.11	2.50	28.47	0.92
1.60-1.70	19.89	5.46	33.60	2.01
1.70-1.80	11.78	3.24	38.27	1.19
1.80-1.90	10.86	2.98	46.13	1.10
1.90-2.00	11.38	3.13	53.04	1.15
>2.00	215.36	59.17	85.26	21.76
	363.97	100.00		

Table 3- 4 Analysis of Fine Spiral Refuse(Size Range:-250µm+150µm,r4=0.1202)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_4 * Wt%
<1.30	27.87	23.62	36.52	2.84
1.30-1.40	6.43	5.45	10.11	0.65
1.40-1.50	5.17	4.38	20.41	0.53
1.50-1.60	6.33	5.36	24.04	0.64
1.60-1.70	3.84	3.25	33.82	0.39
1.70-1.80	1.86	1.58	41.01	0.19
1.80-1.90	2.09	1.77	43.18	0.21
1.90-2.00	5.75	4.87	60.80	0.59
>2.00	58.67	49.72	84.89	5.98
	118.01	100.00		

Table 3- 5 Analysis of Fine Spiral Refuse(Size Range:-150µm,r_4=0.1323)

Specific Gravity Interval	Direct			
	Wt (g)	Wt%	Ash%	r_5* Wt%
<1.30	62.11	47.78	6.86	6.32
1.30-1.40	7.11	5.47	15.79	0.72
1.40-1.50	3.78	2.91	15.83	0.38
1.50-1.60	2.64	2.03	13.34	0.27
1.60-1.70	1.99	1.53	22.24	0.20
1.70-1.80	1.88	1.45	29.80	0.19
1.80-1.90	1.62	1.25	58.43	0.16
1.90-2.00	3.59	2.76	45.91	0.37
>2.00	45.26	34.82	82.56	4.61
	129.98	100.00		

Table 3 Analysis of Fine Spiral Refuse(0.31)

Specific Gravity Interval	Direct	
	wt%	Ash%
< 1.30	15.42	22.08
1.30 - 1.40	4.69	11.14
1.40 - 1.50	4.16	17.01
1.50 - 1.60	2.41	25.07
1.60 - 1.70	3.62	32.63
1.70 - 1.80	2.05	37.70
1.80 - 1.90	2.25	48.58
1.90 - 2.00	2.87	52.91
> 2.00	62.54	84.38
Total	100.00	

APPENDIX D

Weight versus Particle Size and Ash versus Particle Size data

Table 1-1 Analysis of Fine Spiral Clean Coal(Size Range:+1000μm, r_1=0.2338)

Specific Gravity Interval	Direct						Cumulative	
	Wt (g)	Wt%	Ash%	r_1 * Wt%	y_c*r_1 * Wt%	y_c* Ash, %	Wt%	Ash%
<1.30	116.05	50.43	3.53	11.79	6.25	1.87	11.79	3.53
1.30-1.40	67.65	29.40	7.23	6.87	3.64	3.83	18.66	4.89
1.40-1.50	19.79	8.60	15.49	2.01	1.07	8.21	20.67	5.92
1.50-1.60	8.11	3.52	23.13	0.82	0.44	12.26	21.50	6.58
1.60-1.70	6.08	2.64	35.15	0.62	0.33	18.63	22.12	7.38
1.70-1.80	1.58	0.69	40.52	0.16	0.09	21.48	22.28	7.62
1.80-1.90	1.58	0.69	46.77	0.16	0.09	24.79	22.44	7.90
1.90-2.00	0.81	0.35	54.4	0.08	0.04	28.83	22.52	8.07
>2.00	8.47	3.68	83.51	0.86	0.46	44.26	23.38	10.85
Total	230.12	100.00		23.38	12.39			

Table 1-2 Analysis of Fine Spiral Clean Coal(Size Range:-1000μm+600μm,r_2=0.2719)

Specific Gravity Interval	Direct						Cumulative	
	Wt (g)	Wt%	Ash%	r_2 * Wt%	y_c*r_2 * Wt%	y_c* Ash, %	Wt%	Ash%
<1.30	156.73	58.47	2.7	15.90	8.43	1.43	15.90	2.70
1.30-1.40	77.08	28.76	6.35	7.82	4.14	3.37	23.72	3.90
1.40-1.50	20.98	7.83	14.07	2.13	1.13	7.46	25.84	4.74
1.50-1.60	6.54	2.44	22.13	0.66	0.35	11.73	26.51	5.18
1.60-1.70	4.00	1.49	30.73	0.41	0.22	16.29	26.91	5.56
1.70-1.80	1.17	0.44	44.36	0.12	0.06	23.51	27.03	5.73
1.80-1.90	0.49	0.18	51.57	0.05	0.03	27.33	27.08	5.82
1.90-2.00	0.14	0.05	80.67	0.01	0.01	42.76	27.10	5.85
>2.00	0.92	0.34	80.67	0.09	0.05	42.76	27.19	6.11
Total	268.05	100.00		27.19	14.41			

Table 1-3 Analysis of Fine Spiral Clean Coal(Size Range:-600μm+250μm,r_3=0.2775)

Specific Gravity Interval	Direct						Cumulative	
	Wt (g)	Wt%	Ash%	r_1 * Wt%	y_c*r_3 * Wt%	y_c* Ash, %	Wt%	Ash%
<1.30	117.25	43.03	2.04	11.94	6.33	1.08	11.94	2.04
1.30-1.40	128.49	47.15	6.11	13.08	6.93	3.24	25.02	4.17
1.40-1.50	19.81	7.27	13.65	2.02	1.07	7.23	27.04	4.88
1.50-1.60	3.45	1.27	23.67	0.35	0.19	12.55	27.39	5.12
1.60-1.70	1.32	0.48	26.87	0.13	0.07	14.24	27.53	5.22
1.70-1.80	1.64	0.60	34.53	0.17	0.09	18.30	27.70	5.40
1.80-1.90	0.54	0.20	67.04	0.05	0.03	35.53	27.75	5.52
1.90-2.00				0.00	0.00	0.00	27.75	5.52
>2.00				0.00	0.00	0.00	27.75	5.52
Total	272.50	100.00		27.75	14.71			

Table 1-4 Analysis of Fine Spiral Clean Coal(Size Range:-250μm+150μm,r_4=0.0989)

Specific Gravity Interval	Direct						Cumulative	
	Wt (g)	Wt%	Ash%	r_4 * Wt%	y_c*r_4 * Wt%	y_c* Ash, %	Wt%	Ash%
<1.30	36.47	38.24	2.60	3.78	2.00	1.38	3.78	2.60
1.30-1.40	49.56	51.97	5.39	5.14	2.72	2.86	8.92	4.21
1.40-1.50	4.81	5.04	14.48	0.50	0.26	7.67	9.42	4.75
1.50-1.60	1.62	1.70	22.41	0.17	0.09	11.88	9.59	5.06
1.60-1.70	0.63	0.66	29.60	0.07	0.03	15.69	9.65	5.23
1.70-1.80	1.49	1.56	35.04	0.15	0.08	18.57	9.81	5.70
1.80-1.90	0.79	0.83	67.00	0.08	0.04	35.51	9.89	6.20
1.90-2.00	0.00	0.00		0.00	0.00	0.00	9.89	6.20
>2.00	0.00	0.00		0.00	0.00	0.00	9.89	6.20
Total	95.37	100.00		9.89	5.24			

VITA

Meng Yang was born in Penglai County, Shandong Province, People's Republic of China. He graduated from Yantai University, China, receiving his Bachelor Degree in Chemical Engineering in 2000. After graduation, he worked at No. 3521 factory of Chinese People's Liberation Army, as an assistant engineer involved in polymer processing.

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